PB80-187479

Select Topics in Stormwater Management Planning for New Residential Developments

Meta Systems, Inc.
Cambridge, MA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Mar 80

U.S. Department of Commerce
National Technical Information Service
NTIS.

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-80-013
March 1980

PB80-187479

Research and Development

Select Topics in Stormwater Management Planning for New Residential Developments

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/2-80-013

2.

3. RECIPIENT'S ACCESSION NO.
PB80 187479

4. TITLE AND SUBTITLE
SELECT TOPICS IN STORMWATER MANAGEMENT PLANNING FOR NEW RESIDENTIAL DEVELOPMENTS

5. REPORT DATE
March 1980 (Issuing Date)

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Meta Systems, Inc.
Ten Holworthy Street
Cambridge, Massachusetts 02138

10. PROGRAM ELEMENT NO.
1BC822, SOS #2, Task #8

11. CONTRACT/GRANT NO.
R-805238

12. SPONSORING AGENCY NAME AND ADDRESS
Municipal Environmental Research Laboratory--Cin. OH
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED
Final July 1977-January 1979

14. SPONSORING AGENCY CODE
EPA/600/14

15. SUPPLEMENTARY NOTES
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16. ABSTRACT

Several aspects of stormwater management planning for new residential developments are investigated. Areas of research include the evaluation of pollutant accumulation and washoff data using exploratory statistical techniques; simulations to compare the relative effectiveness of various control measures and layout patterns from a small subdivision; formulation of simple stochastic models for stormwater management planning; estimation of cost models for conventional storm sewer systems; and evaluation of institutional and political problems in implementing non-conventional control measures. Analysis of existing data on street surface accumulation and washoff suggests the modification of functional forms and parameter values in current stormwater simulation models such as STORM or SWMM that are used to estimate street loadings and washoff. Simulation studies, used to evaluate the effect of on-site control measures and development layout on runoff, indicate that porous pavement and interactions with subdivision layout are important in controlling runoff. Three simple stochastic models were developed to illustrate their use as preliminary planning tools. As for costs, a planning model that predicts quite accurately conventional drainage costs was developed from an existing data set. Finally, investigation into the institutional aspects of innovative stormwater controls, including two detailed Massachusetts case studies, identified several factors as important in the acceptance of innovation: strength of the housing market; professionalism and technical expertise in government; and city size and geographic region.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Water pollution, Control simulation, Cost effectiveness, Surface water runoff, Mathematical models, Economics, Land use	Residential development, Street surface pollutant accumulation	13B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77)

☆ U.S. GOVERNMENT PRINTING OFFICE 1980-657-146/5619

EPA-600/2-80-013
March 1980

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplied and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research -- a most vital communications link between the research and the user community.

This report concerns the management of stormwater runoff from new residential developments. The authors have examined several problem areas relating to the planning and implementation of non-conventional stormwater control measures in such developments, including 1) the evaluation of pollutant accumulation and washoff data, 2) the development of production and cost functions for stormwater management measures, 3) the formulation of stochastic models for management planning, and 4) identification of political and institutional barriers to implementing non-conventional control measures. By reanalyzing existing data bases, the authors show how improved statistical methods can lead to new interpretations of the pollutant accumulation and washoff processes. Their results suggest how elements of existing models such as STORM and SWMM might be improved, how cost functions can be developed, and how relatively simple stochastic models can be used to screen alternative management strategies. The authors also demonstrate how a simulation study can be used to evaluate alternative on-site management measures and combinations of the literature on innovation in zoning, subdivision regulation, and building codes with experience in two case studies to identify sources of difficulty in implementing innovative control measures.

Francis T. Mayo
Director
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ABSTRACT

Areas of research undertaken in this study included the evaluation of pollutant accumulation and washoff data, development of production functions for stormwater management measures, formulation of simple stochastic models for stormwater management, estimation of cost models for control measures, and evaluation of institutional and political problems in implementing non-conventional control measures.

Analysis of existing data on street surface pollutant accumulation indicated that distributions are log-normal. Previous studies generally ignored this characteristic. Accumulation is a nonlinear process, but is modeled more appropriately by a second order relationship than the first order models previously used. Examination of new washoff data indicated that exponential models such as those incorporated in SWMM can fit individual storms quite well. However, parameters are not constant across storms.

Simulation studies and two-way table analyses were used to evaluate subdivision layout and stormwater control measures. Effects of individual measures were non-additive and interacted with site layout. Porous pavement was the single most effective control measure of those considered, but altering subdivision layout was an equally effective approach.

Three examples of simple stochastic analyses were developed to illustrate their use in preliminary planning: selection of a storm event for drainage management, design of a management system for combined sewage, and prediction of runoff quality.

Using a simplified runoff analysis, a planning model for predicting conventional drainage costs was developed and estimated from an existing data set. The high explanatory power of this model suggests that when adequate cost data are developed, similar models can be developed for non-conventional management measures.

Studies on local acceptance of innovation in subdivisions design and building codes were examined to identify possible problems in implementing new stormwater control measures. Factors affecting the acceptance of innovation included strength of the housing market, professionalism and technical expertise in the government, and city size and geographic region. Similar factors will influence the success of innovation in stormwater management. The report discusses two Massachusetts case studies in detail.

This report was submitted in fulfillment of Grant Number R-805238 by Meta Systems Inc under the sponsorship of the U.S. Environmental Protection Agency. The project extended from July 11, 1977 to January 31, 1979; work was completed by the end of July, 1978.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

acre-ft -- acre-foot
ADT -- average daily traffic flow
BOD$_5$ -- five-day biological oxygen demand
cfs -- cubic feet per second
COD -- chemical oxygen demand
ft(ft^2, ft^3) -- feet (square feet, cubic feet)
ft^3/sec -- cubic feet per second
gal/SY -- gallons per square yard
ha -- hectare
in/hr -- inches per hour
kg -- kilogram
km -- kilometer
lb -- pound
m -- meter
m^3/sec -- cubic meters per second
mg/ℓ -- milligram per liter
min -- minute
R^2 -- coefficient of determination
se -- standard error
TS -- total solids

SYMBOLS

A -- drainage area, in acres
a -- empirical parameter (section 5)
-- multiplier on dry weather flow (D), aD signifies design capacity (section 7)
-- empirical parameter (section 8, defined on page 77)
A_d -- developed acres in drainage area
a_i -- constant in runoff coefficient calculation, evaluated separately for each level of impervious area
A_T -- total drainage area, in acres
a_1, a_2, a_3 -- empirical parameters in general flow formula
α -- empirical parameter
b -- empirical parameter
b_1, b_2 -- empirical parameters in pipe cost equation
β -- empirical parameter
C -- runoff coefficient
c -- empirical parameter
C_B -- cost of providing storage basin
C_D -- damage function associated with stormwater quality and quantity

Cd -- cumulative cadmium loading
$C_i(\ )$ -- present value of costs of control measure i
Cl^- -- cumulative chloride loading
C_p -- pipe cost in dollars per foot (1963 dollars)
Cr -- cumulative chromium loading
C_s -- cost of collection and storage system
C_T -- total cost of storm runoff, in 1963 dollars
c_1, c_2 -- empirical parameters in system length equation
c_3 -- empirical parameter relating A/A_d ratio to total storm cost
D -- dry flow (section 7)
-- pipe diameter in inches (section 8)
D(i) -- damage caused by inundation of property
D_B -- smallest pipe diameter, in inches
D_E -- largest pipe diameter, in inches
D_S, D_W -- locational dummy variables in total cost equation, for southern and western regions of the U.S., respectively
$d_1, d_2, d_3,$
d_4, d_5, d_6 -- empirical parameters in storm runoff total cost equation
E -- pipe costs
e_1, e_2, e_3, e_4 -- empirical parameters in cost per foot equation
f(i) -- density function of rainfall intensity
F(i) -- Frequency function of rainfall intensity
$F_1(\ ), F_2(\ )$ -- production functions relating to control levels and rainfall to water quality and quantity, respectively
Fe -- cumulative iron loading
flow (t) -- flow accumulated up to and including period t, in ft^3
Γ -- gamma function
γ -- empirical parameter
I -- design rainfall intensity, in inches per hour
i -- control measure (section 4)
-- rainfall intensity, in inches per hour (section 7)
I_{15} -- 15 minute storm intensity associated with design storm
i^* -- design rainfall intensity
K -- location specific empirical parameter in rainfall intensity equation
k -- multiple of the increase in a large number of random variables (section 5, p. 20)
-- empirical constant (section 5, p. 40)
-- decay constant (section 5, p. 47)
-- empirical constant (section 7)
k_1 -- accumulation constant
k_2 -- erosion constant
K(i) -- storm sewer cost
L -- solids washoff pounds
L_o -- maximum potential solids washoff
L_T -- total length of drain, in feet
λ -- an empirical parameter, used with r, such that r/λ = mean and r/λ^2 = variance of storm intensity in Gamma distribution
M -- number of inlets and manholes
MS -- mean squared flow
n -- Manning's roughness coefficient

NO_2 -- cumulative nitrite loading
NO_3 -- cumulative nitrate loading
$O\text{-}PO_4$ -- cumulative orthophosphate loading
$P(t)$ -- probability of storm event
P_b -- cumulative lead loading
PO_4 -- cumulative phosphate loading
$Pr\{(D+a)>aD\}$ -- probability that D+a is greater than aD
Q -- storm runoff (section 7)
-- design storm outlet capacity (section 8)
$Q(t)$ -- storm water quantity for rainfall event t
$q(t)$ -- storm water quality standard for rainfall event t
r -- an empirical parameter, used with λ such that r/λ = mean, and r/λ^2 = variance of storm intensity (section 7, p. 70)
-- runoff in inches per hour (section 7, p. 71)
r_1 -- runoff inches/time in period 1
r_2 -- runoff inches/time in period 2
S -- average slope, in percent
ss -- cumulative suspended solids loading
ss_t -- suspended solids, in lbs., accumulated up to period t
T -- storm frequency, in years
T^* -- design storm frequency, in years
-- index of rainfall event (some combination of duration, intensity, etc.) (section 4)
-- time (section 5, p. 32)
t -- time, in minutes (section 5, p. 49)
TOC -- cumulative total organic carbon loading
TKN -- cumulative total Kjeldahl nitrogen loading
t_1 -- elapsed time from storm start, time 1 (hours)
t_2 -- elapsed time from storm start, time 2 (hours)
U -- pipe utilization factor
U_o -- maximum pipe utilization factor
V -- runoff volume
VSS -- total volatile suspended solids loading
x -- empirical parameter (section 8)
x_1, x_2 -- empirical parameters
Z -- total cost of storm runoff
z -- random variable
Z_i -- set of random variables

ACKNOWLEDGMENTS

BSC Engineering and in particular Robert Daylor and John Thomas provided valuable information on stormwater control measures and development costs. They also contributed the case studies in Section 9. Alfred Leonard, our research assistant, performed a substantial amount of the statistical analysis on the accumulation and washoff data. Chi-Yuan Fan and Douglas Ammon, Project Officers and Richard Field, Chief, Storm and Combined Sewer Section, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, provided helpful guidance.

We would also like to thank Byron Lord of the Department of Transportation, and Nic Kobriger of Envirex, Inc., for permission to use the Envirex-DOT data analyzed in Section 5, and Robert Pitt of Woodward-Clyde Consultants for the use of the San Jose street cleaning data.

Our special thanks to Dianne C. Wood, who organized the preparation and production of the final report. Her careful supervision improved both the appearance and content of the document.

SECTION 1

INTRODUCTION

According to U.S. Census Bureau estimates, the population of the United States is expected to grow from 203 million in 1970 to 264 million in 2000. If the average household size remains constant, 18 million additional dwelling units will be needed by the year 2000 -- a 30 percent increase. Replacement of attrition in the existing housing stock may require roughly an equal number of new units. In other words, a substantial proportion of the nation's housing stock in the year 2000 will have been constructed over the next 20 years. Thus the manner in which these new units are designed, constructed, and maintained will be an important factor in the contribution of the residential sector to the nation's environmental quality. To the extent that proper planning today can mitigate possible adverse consequences of such new development, environmental quality can be preserved and enhanced. This report deals with one aspect of the environmental consequences of new development: the impact of stormwater runoff and the management of that impact.

Unfortunately, it is not possible today to develop a manual or handbook that will routinely and accurately predict the runoff impacts from various types of new development and prescribe cost-effective mitigation measures. The state of knowledge in several crucial areas, although improving rapidly, is not yet well-enough developed. This study has had a much more modest goal: to develop methodologies and approaches for dealing with several selected aspects of the planning problem.

1. The development of improved methods for estimating pollutant accumulation and washoff from street surfaces

The accumulation and washoff functions currently used in stormwater quality computations are crucial elements in such computations, yet both the basic formulations and the techniques used to estimate parameters for these formulations can be questioned. Using a variety of statistical techniques, this study has reexamined much of the existing data in these areas and has begun an exploratory analysis of newly acquired data.

2. The development of production functions for describing the effectiveness of stormwater control measures and site layout patterns

Virtually no actual data exist from which such performance measures can be estimated. Our approach was to simulate the effects of various control measures and layout patterns on runoff from a small subdivision. The results of these simulations were then used to explore methods for summarizing the impacts of various alternatives.

3. The formulation of stochastic models for stormwater management

Since stormwater runoff events are inherently stochastic, relatively simple probabilistic models may be formulated for many planning purposes to capture the essence of the decision problem. Several such models were formulated in this study and are discussed in this report.

4. The estimation of cost models for control measures

In order to develop general guidelines for stormwater management in new developments, planners require cost models which can be employed at a preliminary planning level in the absence of detailed engineering design data. This study investigated how such models can be developed and estimated, using as a specific example the costs of conventional stormwater drainage systems.

5. The evaluation of institutional and political problems in implementing non-conventional control measures

Two case studies of non-conventional approaches were examined. Both are small subdivisions in eastern Massachusetts and incorporate porous pavement in their design. The report describes the problems encountered by the developer in gaining approval for these designs and places them in context by discussing the general problems of innovation in residential development.
A closely related issue is that of allocating the costs of stormwater management among the affected parties. Drawing upon the general economic literature, this report discusses some of the basic principles for evaluating various allocation mechanisms.

SECTION 2

CONCLUSIONS

ANALYSIS OF ACCUMULATION AND WASHOFF DATA

- Our reanalysis of available pollutant accumulation data for street surfaces indicates that loadings follow log-normal distributions. This is true both of solids and specific pollutants. Previous studies have ignored the nature of the frequency distribution, and as a consequence their reported summary statistics are often misleading.

- Models for explaining the solids and pollutant accumulation as a function of variables describing land use, traffic, and geography can be developed using the technique of two-way tables. Our results suggest that average daily traffic is a consistently important variable. Solids loadings tend to decrease with increasing traffic levels. These results suggest that scouring is an important mechanism affecting accumulation. In the case of lead, loadings first increased then decreased with increasing traffic volume, suggesting that both deposition and scour are important factors. Other variables were less consistently related to accumulation. In general the unexplained variation in these models was high -- on the order of the effects of the variables themselves. Thus with the present data base, detailed predictive models are not feasible. Outside of a possible correction for traffic volume, there is no reason to use other than median (or some typical value) accumulation values.

- An examination of the available data on accumulation over time indicates that the process is nonlinear; accumulation is initially rapid and then tapers off. The process is not well-modeled by a simple first order process, as has been commonly assumed. A second order accumulation model appears to be more appropriate. The data also suggest that since the bulk of the material accumulates within the first day, street sweeping would have to be very frequent to be effective as a water quality management practice.

- Analysis of washoff data indicates that accumulated pollutant loads from individual storms can be modeled as a function of accumulated washoff using log linear formulations or exponential models similar in structure to those in STORM and SWMM. However, the parameters vary widely across both watersheds and storms within the same watershed.

CONSTRUCTING PRODUCTION FUNCTIONS FOR ON-SITE CONTROL MEASURES

Given the lack of actual data on on-site stormwater controls, simulation studies can be used to compare the relative effectiveness of sets of controls. However, the results of these studies should not be viewed as being representative of the real performance of control measures.

- Because of interactions among control measures and among controls and development types, analysis of variance or two-way table methods are a prerequisite for a proper analysis of the effects of control measures and development layouts.
- For the set of three residential developments considered, the simulations indicate that porous pavement is the most effective single control measure in reducing peak and total flow and peak and total solids washoff. Flows and solids are about 25-35 percent of the base case (no controls). Additional controls (swales, roof drain disconnection), account for an additional ten percent. Control measure effects are not additive; use of additional controls beyond two shows diminishing return (zero-one percent further reduction). Vegetative cover is an exception, reducing solids washoff even when used with two or three other controls already in place.
- Cluster development lowers flow or solids 12 to 15 percent compared to conventional developments with the same number of total housing units.
- The interaction between on-site controls and developments is multiplicative. Therefore, by carefully planning the proper combinations of control measures and development layouts, substantial reductions in stormwater runoff may be effected. This is a key finding for the planning of new residential developments.

COST MODELS

- Relatively simple models based on a physical model of runoff control can be estimated to explain the costs of stormwater management facilities. Such models explained 60 to 90 percent of the variation in costs in an available data set depending upon the extent of detailed hydrologic information assumed.

STOCHASTIC MODELS

- For preliminary planning and regional studies, relatively simple stochastic models can prove to be useful adjuncts or alternatives to simulation approaches. Examples illustrated in this report are selecting planning events for drainage facilities, evaluating design alternatives for combined sewer systems, and computing the expected loading from runoff events.

INSTITUTIONAL AND POLITICAL ISSUES

- Factors that influence the acceptance of innovations in residential development include the strength of the local housing market, the degree of professionalism among city officials and agency personnel, the size of the city, and the region of the country. Major difficulties in the case of planned unit development (PUD) ordinances and new building codes arise when special interest groups feel threatened by new innovations. It is anticipated that these patterns will assert themselves in the case of stormwater management innovations. In two cases a developer (BSC Engineering) was able to convince Massachusetts towns to accept innovative measures after meeting considerable initial resistance. A crucial element in gaining acceptance for the plans was the developer's ability to convince town officials that the full risks of the designs would fall on the developments. In both cases the innovative measures required considerably more time for approval than would conventional designs.

SECTION 3

RECOMMENDATIONS

ACCUMULATION AND WASHOFF DATA

- Runoff quality predictions are sensitive to street loading. Our analysis indicates that there is considerable unexplained variation in the existing data. This may be due either to the inherent variability in the processes involved or inadequate models. More data and continuing analysis using resistant statistics are needed to resolve this question.

- Further consideration should be given for incorporation in STORM and SWMM of a second order model accumulation relationship such as the one developed in this report.

PRODUCTION FUNCTIONS FOR ON-SITE CONTROL MEASURES

- In planning on-site management measures, the subdivision layout should be considered carefully, since such measures can be at least as effective as control technologies and can influence the effectiveness of such technologies.

- While simulation studies can be used to explore techniques for fitting production functions and to suggest the relative effectiveness of alternative measures, there is a lack of data for verifying such studies. A high priority should be given to obtaining data on the effectiveness of control measures. Porous pavement in particular looks very attractive and should receive accelerated study.

STOCHASTIC MODELS

- Stochastic models can be used effectively in preliminary planning studies. However, this type of analysis has been under-utilized in the past because planners and designers lack familiarity with the techniques involved. EPA planning materials and manuals should incorporate models similar to those discussed in this report and discuss the nature and limitations of their use.

COST FUNCTIONS

- In order to develop general cost models for non-conventional control measures, a set of synthetic cost data should be developed that represents the range of control measures, development types, and site conditions likely to be encountered in practice.

INSTITUTIONAL AND POLITICAL ISSUES

- Some type of legislative action may be necessary to minimize resistance to innovative control measures at the local level. Such action might range from educational programs and model regulations to a program of encouraging states to enact preemptive legislation (as was done by Operation Breakthrough). 208 agencies would be appropriate vehicles for educational programs.

SECTION 4

ALTERNATIVES FOR THE CONTROL OF STORMWATER QUANTITY AND QUALITY

TYPES OF CONTROL MEASURES

Once it is recognized that the objective of stormwater management is not solely to remove runoff from the site as quickly as possible, a large variety of alternative approaches become available to planners and engineers. These measures may alter the runoff peak, the total quantity of runoff, and/or the runoff quality and may also provide additional secondary benefits to the developer and residents of a subdivision. Of course, each measure is also associated with a vector of primary and secondary costs. Thus the task of the engineer is generally perceived as that of selecting a measure or combination of measures to meet a set of objectives (described in terms of runoff quantity and quality and possibly other secondary benefits) while minimizing the costs. More generally, the objective might be specified as maximizing net benefits. In either case a necessary first step in the analysis must be an enumeration of the options available and their general characteristics. In this section we present such a description, and, as an introduction to the remainder of the report, discuss some of the current limitations to carrying forward the complete analysis.

Table 4-1 presents a list of control measures, organized by principal control mechanism and described in terms of a variety of positive impacts (benefits) and negative impacts (costs). Considered in these categories are not only monetary costs and the primary impacts upon water quality, but also secondary benefits and costs commonly or necessarily associated with these measures. Three types of primary benefits are included. Measures that reduce the peak or total quantity of flow enhance the ability of downstream works to treat the runoff, while measures that remove pollutants (chiefly suspended solids) directly enhance water quality.

The allocation of costs among the relevant interests is not a simple matter. For a discussion of different methodologies, see Appendix E.

The major control mechanisms are as follows:

Storage/Detention. Measures that provide a means to capture and store runoff for some period of time.

Overland Flow Modification. Measures that influence the rate of runoff by altering the velocity or direction of overland flow.

Infiltration. Measures that increase the ability of the ground to accept stormwater by infiltration.

TABLE 4-1. STORMWATER CONTROL MEASURES

	Benefits									Costs									
	Primary			Secondary															
	Reduction of Peak Discharge	Reduction of Total Discharges	Control of Water Quality	Flood Protection	Recreation	Groundwater Recharge	Aquatic/Wildlife Enhancement	Aesthetic	Other Beneficial Water Uses	High Capital Expenses	High Maintenance Expense	Structural Mod. to Building	Possible Structural Damage	Public Health/ Safety	Mosquito Breeding	Groundwater Pollution	Large Land Requirements	Increased Erosion Potential	Interference with Activities
Storage																			
Rooftop	X			X					X	X	X	X	X						
Parking Lot	X			X							X								X
Wet Detention Basins	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X		
Dry Detention Basins	X	X	X	X	X	X				X	X				X	X	X		
Underground	X		X	X					X	X	X								
House Lot	X	X	X	X		X					X		X		X	X			X
Small Dikes, Traps, etc.	X		X	X							X								X
Fountains	X		X	X				X		X	X								
Infiltration																			
Trenches	X	X		X		X						X				X			
Pits	X	X		X		X						X				X			
Porous Pavement																			
Roads	X	X		X		X				X	X					X			X
Driveways	X	X		X		X				X	X					X			
Sidewalks	X	X		X		X				X	X								
Parking	X	X		X		X				X	X					X			X
Gravel																			
Roads	X	X		X		X					X					X			X
Driveways	X	X		X		X					X					X			

X - Possible or likely impact.

TABLE 4-1. (CONTINUED)

	Benefits									Costs										
	Primary			Secondary																
	Reduction of Peak Discharge	Reduction of Total Discharges	Control of Water Quality	Flood Protection	Recreation	Groundwater Recharge	Aquatic/Wildlife Enhancement	Aesthetic	Other Beneficial Water Uses	High Capital Expenses	High Mainten-ance Expense	Structural Mod. to Building	Possible Struc-tural Damage	Public Health/ Safety	Mosquito Breeding	Groundwater Pollution	Large Land Requirements	Increased Ero-sion Potential	Interference with Activities	
Gravel (continued)																				
Sidewalks	X	X		X		X					X									
Parking Areas	X	X		X		X					X					X			X	
Grass Crib	X	X		X		X										X			X	
Vegetated Depressions	X	X		X		X		X			X				X	X			X	
Overland Flow Modification																				
Diversion	X		X								X									
Surface Roughening	X		X	X																
Level Spreader	X		X								X									
Grade Stabilization	X		X	X						X										
Swales	X	X	X	X				X			X									
Gutter Placement	X	X		X														X		
Increased Roof Roughness	X			X								X								
Rooftop Gardens	X	X		X			X	X		X	X	X								
Rippled Pavement	X			X															X	
Soil Stabilization																				
Grass & Shrubs	X	X	X	X		X	X	X			X									
Organic & Inorganic Mulches	X	X	X	X		X				X										

TABLE 4-1. (CONTINUED)

	Benefits									Costs										
	Primary			Secondary																
	Reduction of Peak Discharge	Reduction of Total Discharges	Control of Water Quality	Flood Protection	Recreation	Groundwater Recharge	Aquatic/Wildlife Enhancement	Aesthetic	Other Beneficial Water Uses	High Capital Expenses	High Mainten-ance Expense	Structural Mod. to Building	Possible Struc-tural Damage	Public Health/ Safety	Mosquito Breeding	Groundwater Pollution	Large Land Requirements	Increased Ero-sion Potential	Interference with Activities
Soil Stabilization (continued)																			
Chemical Tackifiers			X							X									
Hydromulching	X	X	X	X		X				X									
Management																			
Street Cleaning			X					X			X								
Sewer Flushing			X								X								
Sewer Flow Control	X			X							X								
Cleaning of Catch Basins			X								X								
Filtration																			
Drain Filters	X		X								X								
Straw or Hay Bales	X		X								X								

Sources: Poertner (1974); Soil Conservation Service (1975); Engineering Science (1975); Hittman Associates (1976); ULI, ASCE, and NAHB (1975); Fairfax County, Va. (1974).

Soil Stabilization. Measures that reduce soil erosion by binding the soil particles and/or by dissipating the energy of falling rain drops.

Filtration. Measures that strain suspended sediment particles from stormwater flow.

Management. Measures that maintain or operate existing infrastructure to alter the timing of stormwater flows and reduce their pollution potential.

In Table 4-1 measures have been classified according to their principal mechanisms as listed above, but it should be understood that certain measures might involve more than one mechanism. For example, while grasses and mulch provide direct stabilization of the soil, they also alter the pattern of overland flow by providing higher flow resistance than does bare soil. If properly maintained, certain types of storage basins will greatly enhance infiltration. Thus the categories presented are not necessarily mutually exclusive, but are intended to highlight the principal mechanisms of control.

Table 4-1 provides an indication of which costs and benefits have been attributed to specific measures. No attempt is made to quantify these attributes, either in relative or absolute terms. Methods for quantifying certain of the attributes, particularly the primary benefits and costs, will be discussed in later sections of the report. Other impacts can be assessed only qualitatively. Further, some of the adverse impacts indicated in the table can be alleviated with proper management. For example, the water level in a wet basin can be controlled to eliminate mosquito breeding. Table 4-1 is intended to be a framework for later analyses and the selection of combinations of measures. The paragraphs below discuss by mechanism the major areas of benefits and costs that have been identified.

Stormwater storage measures reduce stormwater peaks by dampening extreme storm flows and improve the quality of the water by providing a period of time for the larger suspended particles to settle out. Generally, storage measures do not reduce the total quantity of flow, although depending on the facility type there may be some reduction through evaporation or infiltration. The secondary benefits of storage facilities depend upon the scale of the facilities and their management. The larger wet storage basins have the greatest potential for beneficial impacts, providing a variety of opportunities for recreational uses, a possible habitat for aquatic organisms, and aesthetic enhancement of a site. All storage measures provide some degree of flood protection as do all other measures that reduce peak flow. However, stormwater quality improvement and flood protection are not completely complementary. For example, if the first flush of pollutants is significant, it might be desirable from a quality standpoint to retain the early flows long enough to achieve maximum removal by settling. Flood control objectives, on the other hand, might dictate discharging the early flows as rapidly as possible in anticipation of later peaks. There are some opportunities for water reuse using storage measures, although additional treatment may be necessary depending upon the nature of the reuse.

Most storage measures have significant capital costs and operating and maintenance expenses associated with cleaning sediment and debris from the facilities and adjacent areas. Wet basins need particularly good maintenance in order to obtain the full range of potential benefits. Also there may be health, safety and insect problems associated with standing bodies of water. Storage facilities that comprise a secondary use of some facility, such as parking lots, backyards or roadways, tend to be the least expensive in terms of direct capital costs, but may lower the value of the facility for its principal use.

Infiltration measures reduce both the peak and total flow and in the process provide a means for enhanced groundwater recharge. Because of the contamination of urban stormwater by toxic organic and inorganic materials (Colston, 1974) there exists a potential groundwater contamination problem which has not been fully assessed.

Overland flow modification measures are generally small in scale and must be implemented extensively to have a significant impact on a development. Some of these measures serve chiefly to enhance water quality by reducing the erosion potential of overland flow, while others act primarily to alter the timing, and, to some extent, the quantity of runoff. Swales provide all three primary benefits and in addition may be preferred on aesthetic grounds to traditional curbs, since they help preserve the natural character of lower density development.

Drain filters and bales are used mainly to remove sediment from construction site runoff. They also provide some attenuation of runoff peaks, but are employed as temporary measures only. Cleaning after each storm is necessary, particularly for drain filters.

Most soil stabilization measures enhance infiltration and alter runoff patterns. Grass and shrubs may be employed either as temporary or permanent stabilization measures, while mulches and tackifiers may be employed to stabilize and protect the soil until a vegetative cover can develop and mature. These measures increase the capital costs of site development, but can be cost-effective when compared with downstream removal of deposited sediments (Engineering Science, Inc., 1973).

Management methods have been directed primarily at quality improvement and generally have high operating costs. Sewer flow management systems employ the storage capacity of sewers to attenuate the storm peak flows and thus enhance the capacity of treatment plants to remove pollutants. Aesthetic improvement is listed in Table 4-1 as a secondary impact of street cleaning. Of course, street cleaning as practiced today is primarily intended for its aesthetic effects and probably has little impact on stormwater quality (URS, 1974).

SUBDIVISION DESIGN

The distinction between new and existing residential developments is a factor in stormwater management decisions for two reasons. First, existing developments impose structural limitations on the types of options that can be considered. There may not be enough room for detention basins, for example. In theory these limitations do not apply to new subdivisions, although in practice the options available to the designer depend upon the point in the subdivision process at which stormwater management is considered. If little or no thought is given to this factor until after all the important layout and structural decisions have been made, then for all practical purposes the designer may be as limited as in an existing development.

A second opportunity that is available only for new developments is the management of stormwater through the basic layout of the subdivision itself. For example, by clustering dwelling units (that is, using smaller lot sizes in return for preserving common open space), the length of road network and hence the impervious area can be greatly reduced. An example from the Costs of Sprawl (Real Estate Research Corporation, 1974) illustrates the type of savings involved. For 1000 single family homes in a conventional subdivision with one-third acre (1,344 square meters) lots, 60,000 feet (18,293 meters) of streets would be required, covering 37 acres (149,233 square meters) of land. If the same homes were clustered on one-fifth acre (807 square meter) lots, 44,750 feet (13,643 meters) of street would be required, covering 31 acres (125,033 square meters) -- 16 percent less than the conventional layout. With more intensive clustering (e.g., the use of townhouses) even greater savings are possible. If the clustered layout has the same gross density as the conventional subdivision, the reduction in street surface would be translated into open space and thus a reduction in overall impervious area. In general, this would lead to reduced runoff from the site and make possible the preservation of natural drainage and wetland areas that provide natural treatment for the runoff.

In clustered subdivisions, however, activities are more concentrated; accumulation of street pollutant per curb mile could be greater than in conventional layouts. These considerations may attenuate the advantages of clustering to some extent, but there are no data upon which to base an assessment of these possibilities. In general, it is still likely that layout patterns which minimize impervious area are beneficial to stormwater quality by keeping gross population density constant. Without a quantitative measure of the effectiveness of clustering, it is not possible to compare the stormwater impacts of a conventional subdivision against a clustered design with a higher gross density.

SELECTION OF CONTROL MECHANISMS

If the secondary costs and benefits of stormwater control are ignored for the moment, the problem of selecting the scale or activity level for the various stormwater control measures can be stated as a problem of minimizing the expected costs of runoff events:

$$\text{minimize:} \quad \sum_{t} C_D(q(t),Q(t))\, p(t) + \sum_{i=1}^{N} C_i(X_i) \qquad (4\text{-}1)$$

$$\text{subject to:} \quad q(t) = F_1(X_1, \ldots X_N), \qquad (4\text{-}2)$$

$$Q(t) = F_2(X_1, \ldots X_N), \qquad (4\text{-}3)$$

where $q(t)$ = stormwater quality standard for rainfall event t,

$Q(t)$ = stormwater quantity for rainfall event t,

X_i = level of control measure i, i = 1, ... N (N = total number of measures),

C_D = damage function associated with stormwater quality and quantity; this cost may reflect the costs of conveyance and treatment to some prescribed level of quality, or more generally, the damages associated with water quality deterioration,

t = index of rainfall event, which may be appropriately defined by some combination of duration, intensity, antecedent conditions, etc.,

$C_i(\ )$ = present value of costs of control measure i,

$F_1(\ ), F_2(\ )$ = production functions relating control levels and rainfall to water quality and quantity, respectively, for storm event t, and

$p(t)$ = probability of storm event t.

While equations (4-1) to (4-3) are conceptually straightforward, it is difficult to plan stormwater control measures based directly on this approach for the simple reason that the necessary technological and economic linkages are not yet well-established. This statement is particularly true for new developments, but applies to existing areas as well. In addition to these technical considerations, planners recognize that a variety of political and institutional factors impinge upon the environmental decision-making process and that a solution to the design problem which does not take these factors into account could be unworkable in practice. This is true for all environmental control measures, but stormwater management poses some unique problems because of the degree to which local governments, as opposed to state or federal agencies, control the design process through zoning ordinances, subdivision codes, and building standards.

In moving from a simple enumeration of options such as Table 4-1 to a selection of appropriate measures for a specific location or region, a variety of obstacles must be overcome. In succeeding sections of this report we examine in detail selected problems that appear to pose special difficulties in the planning of stormwater management for new subdivisions.

SECTION 5

ANALYSIS OF LOADING AND WASHOFF DATA

INTRODUCTION

Two basic strategies have been adopted in gathering data for use in quantifying urban stormwater pollutant loadings (see Appendix A). One strategy has focused on measuring the accumulation and composition of dust and dirt on street surfaces. The other has focused on "end of pipe" or waterway measurements of flow and concentration during storm periods. While data from both strategies have been combined and analyzed (URS, 1974), it is unfortunate that to our knowledge only a few studies (Pitt, Woodward-Clyde Consultants, 1977; Envirex-Department of Transportation, 1977) are being performed in which both types of measurements are employed simultaneously in the same study area. Such data would provide a basis for development of a mass balance for quantitative comparisons of the two measurement strategies.

It is evident that differences between the two strategies and general problems associated with measurement and data reduction have considerably hindered attempts to develop statistical models for use in predicting nonpoint source loadings or in calibrating theoretical runoff models.

As discussed in Appendix A, one of the major studies which attempted analysis and model development was done by URS. It utilized univariate statistical techniques in its intensive analysis. But a basic problem in applying univariate analytical strategy is that it could easily have led to false causal inferences, considering the multicollinearity in the data. The authors noted that a multivariate analysis (e.g., analysis of covariance) would have been more desirable, but they considered the data insufficient. Apparently, other analytical strategies, such as multiple regression analysis using dummy variables to represent various classes (e.g., Northwest climatic region or industrial land use), or a robust two-way table approach, were also rejected by the authors for similar reasons. Thus, in general, most investigations of urban pollutant loadings from nonpoint sources are considered to have yielded disappointing results to date. For example, Singh concluded at the 1977 ASCE meeting

> The main objective of this study was to determine the rates at which solids accumulate on street surfaces...Initial efforts in fitting simple conceptual models and use of regression analysis were unsuccessful due to extreme scatter in data...

One can argue that the error lies in looking at "extreme scatter in data" as a nuisance rather than the interesting property of loading rates. Why is there such scatter? For that matter, is there really such scatter? There is confusion in the literature; for example, Singh (1977) as well as Colston (1974), Whipple (1976), and Hammer (1976) find no correlation between elapsed days of accumulation and pollutant concentrations. Sutherland and McCuen (1975) claim the reverse. In part these contradictions are due to sloppiness in the definition of "concentrations" and the failure to consider the collinear effects between independent variables; but there is also real uncertainty in the physical systems being modeled.

Considering the current lack of a thorough understanding of the accumulation/washoff processes, any kind of straightforward regression technique is doomed to failure. Therefore methods designed to discover something about loading rates should be based on the following premises:

1) Exploratory, rather than predictive data analysis; and
2) Stochastic, rather than deterministic model building.

The exploratory process partially relieves us from the burden of having a specific explanatory model of the data at hand; the stochastic premise is similar -- it throws everything we cannot specifically describe into a lumped box of noise. Actually, the two premises are not distinct, since we use either one to guide the other.

EXPLORATORY DATA ANALYSIS

The commentary on urban loading rates (e.g., Sartor and Boyd, 1972; Hammer, 1976; URS, 1974) invariably mentions their extreme range. As a typical example, the URS data for residential loading rates (lbs/curb-mile-day) shows a range of 8-770 (2.25-217.09 kg/curb-km-day), with a standard deviation of 195 (54.98 kg/curb-km-day). For most categories of land use, climate, and traffic patterns, the coefficient of variation (standard deviation/mean) is greater than 1, indicating large variability. This variability in the loading rates was examined by using the URS data, which is a summary of all major studies done before 1974 (all raw data normalized to lbs/curb-mile-day).

Figures 5-1 and 5-2 show the residential suspended solids loadings of the URS study in raw form and organized into a stem-and-leaf display.[1]

In the spirit of exploratory analysis, we make two preliminary remarks about the completed stem-and-leaf display of the residential loading rates shown in the figures:

1) The data are skewed; this immediately makes questionable the use of the standard deviation as a confidence-interval estimate (as was done by Singh, 1977), or the use of regression

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[1] The basic purpose of such displays is to arrange raw data into roughly numerical order -- like a histogram -- so that one can easily answer questions such as: what is the largest value? the smallest? what does the distribution of values look like? Unlike a histogram, however, the display retains some of the identity of the original data by using the actual digits of the data values to construct the display. This makes it easier to see which data value is located where in the histogram (See Appendix A for details).

FIGURE 5-1. RAW DATA: RESIDENTIAL LOADING RATES
URS LBS/CURB-MILE-DAY

400	600	390	210	170	019	032
121	148	081	062	121	135	148
019	020	096	153	060	022	
032	035	024	033	041	028	
070	092	2700	690	260	860	
220	372	659	418	70	85	24
77	238	18	34	103	93	40
770	950	205	950	100	67	93
33	11	8	3	295	31	165
13	69	17	27	18	6	8
39	45	22	12			

Number of observations = 71

FIGURE 5-2. STEM-AND-LEAF DISPLAY, RESIDENTIAL LOADING RATES†
(LBS/CURB-MILE-DAY)

```
loading rate x 0.1
     27**|0 Milwaukee
         |
     10**|
         |55
      9  |
         |6
      8  |
         |7
      7  |          Number of Observations = 71
         |95
      6  |0         Results††: upper hinge: 205(57.80
                                            kg/curb-km-day)
      5  |                          median: 70(19.74
                                            kg/curb-km-day)
      4  |01
         |97                  lower hinge: 27(7.61)
      3  |69                       spread: 178(46.52)
      2  |1230
         |756
      1  |2423400
         |8696797879696
      0**|13122332342213421003112100342l
```

---

†URS, 1974.

††median: the data value half-way in from either end; half the data lie above or below this data point.

hinge: upper (lower)--half-way from the high(low) data extreme to the median, i.e., three-quarters (or one-quarter) of the data are below this point.

spread: difference between upper and lower hinges, i.e., contains one-half of the data.

analysis without data transformation. Specifically, the shape is suggestive of a log-normal distribution (see below).

2) If we calculate the median of the data, it is 70 (19.74). URS reported a <u>mean</u> of 149 (42.01), revealing the skew of the data. (As a comparison, the geometric mean -- essentially a log transformation of the data -- gives a value of 84 (23.68)). Reporting only this arithmetic <u>mean</u> plus a standard deviation of 195 (54.98) is misleading; it says that about 67 percent of the data was between 149 and 195 (42.01 and 54.98). If fact, the true mean is even larger, since URS threw out the highest and lowest values in each group of data. Using the full data, the mean is 201.3 and the standard deviation is 379.7 (56.75 and 107.05). We can see that the mean does a very poor job of summarizing the center of the data. We can also calculate the upper and lower "quarters" of the data to get an idea of how it is spread out, rather than use the standard deviation. If we calculate these <u>hinges</u> (see Figure 5-3), one-half of all data falls within this range. In general, this kind of analysis by medians is much less sensitive (i.e., the analysis is robust) to extreme fluctuations in data.

Most importantly, however, the data look log-normally distributed. If we take logarithms of the loading rates, the resulting display (Figure 5-3) seems much more well-behaved. First, it is symmetric (mean 4.32 (3.05), close to median 4.24 (2.98)) and even somewhat "normal-looking;" second, the data do not appear so "wild" except for the prominently high value of 7.9 (6.63) from Milwaukee. Now we can use more confidently the mean of 4.32 (3.05) and standard deviation of 1.397 (0.13) as summary figures for solids

FIGURE 5-3. LN (RESIDENTIAL LOADING RATES)[†]
(LBS/CURB-MILE-DAY)

```
7* |9
7  |
6* |56788
6  |034
5* |56999
5  |0113334
4* |55556677999
4  |012222334
3* |556678
3  |00112344444                        (ln scale)
2* |5888999      Results: upper hinge: 5.32(4.05)
2  |0034                       median: 4.25(2.98)
1* |7                     lower hinge: 3.29(2.02)
1  |0                          spread: 2.03(0.76)

                                 mean: 4.32(3.05)
                        standard
                        deviation: 1.397(0.13)
```

[†] URS, 1974.

loading rates. What is more, the log-normal distribution suggests an underlying model of the accumulation process. The standard explanation is this: suppose the <u>increase</u> in loading, Δx, is some multiple, k, of the increase in a large number of other variables (z), about most of which we don't know, i.e., $\Delta x = kz_i x$; and suppose the z_i's are random variables. Then the sum of the z's is the sum of these changes in x:

$$z = \sum z_i = \frac{1}{k} \int_{x_1}^{x} \frac{dx}{x} = \frac{1}{k} \log \frac{x}{x_1}$$

The random variable z, being the sum of many random variables, is, by the central limit theorem, normally distributed; and the loading x, log-normally distributed. Therefore, if the observed loading is the multiplicative effect of many factors, we will see the kind of pattern displayed in Figure 5-3.

One question that should be asked at this point is whether this effect is found with other constituents. A problem is that often there are too few measurements for materials such as heavy metals to reveal a distinct pattern to their distribution. When there is a sufficient sample size, the log-normal distribution seems to appear. An excellent example is COD (Figure 5-4). Mean COD loading is 90936 micrograms/gram/day, but this value is greater than almost three-quarters of the data (the upper hinge is 91700) and far larger than the median of 46000 (the URS mean is 82000, differing because of the removal of extreme values by URS). After a log-normal transformation the mean is 10.97; the median, 10.74. The transformation does a good job of making the data symmetric.

FIGURE 5-4. RESIDENTIAL COD MICROGRAMS/GRAM (URS, 1974)

```
 COD x .001
     5  |1
     4**|
     3  |1
     2**|9700

       .|2
    18  |
       .|
    16  |
       .|8
    14  |
       .|
    12* |                upper hinge = 91700
       .|4                    median = 46000
    10  |                lower hinge = 30000
       .|11
     8* |                       mean = 90935.9
       .|2                 standard
     6  |5118              deviation = 105749.
       .|308
     4* |560
       .|24244082
     2  |9441064
       .|88
     0* |
```

To summarize, detailed examination of the distribution of loadings for the constituents COD, Pb, cadmium, organic nitrogen, orthophosphate (O-PO_4), and nitrate reveals generally a log-normal pattern. (See figures in Appendix A for representative stem-and-leaf displays). Exceptions are usually found where the sample size is small (less than 20); this is to be expected from statistical considerations. In most cases log-transformations do a good job of making the data more symmetrical. We can conclude from this that the reported mean values and standard deviations are not good values to use for summarizing loading rates. Use of log-transforms, along with medians, is suggested. Table 5-1 gives a summary of the findings.

TABLE 5-1. COMPARISON OF RESILIENT VS. URS RESULTS,
URBAN STREET LOADINGS
(MICROGRAMS/GRAM UNLESS OTHERWISE NOTED)

Material	Median Value	Mean	URS Reported Mean*	Number of Cases	Comments on Distribution
Residential Suspended Solids (lbs/day)	70	201	149	71	log-normal
Residential COD	46000	90935.9	82000	39	log transform is appropriate
Residential O-PO_4	635		936	42	looks somewhat uniform, not normal after log transform (it is symmetric)
Residential Cd	2.7	3.05	3.0	50	log transform is appropriate
Residential Pb	1100		1484.66	53	log transform is appropriate
Residential NO_3	544		550	20	ln transform is appropriate (1 stray value = Lawrence, Mass.)
Residential Organic N	1950	1779	1880	26	skewed opposite from all others (a few extreme values)
Commercial COD	177000		269000	16	not normal-looking after log transform (small number of cases)
Commercial O-PO_4	14.88		22.50	15	more uniform after log transform
Commercial Pb	3312		3400	17	log transform is appropriate

*URS mean different because extreme values are not included.

TABLE 5-1 (CONTINUED)

Material	Median Value	Mean	URS Reported Mean*	Number of Cases	Comments on Distribution
Commercial NO_3	1259		158	14	symmetrical after ln transform
All Industrial COD	73000		88000	11	symmetrical, but not normal-looking
All Industrial O-PO_4	1400		1250	11	very scattered
All Industrial Pb	1100		1160	24	log transform not quite normal-looking (square root transform better)
All Industrial NO_3	410		246	7	very scattered distribution (small number of cases)

*URS mean different because extreme values are not included.

ANALYSIS BY TWO-WAY TABLES

The model described above assumes that the processes that account for the observed loading on streets are numerous and otherwise unanalyzable, that is, a black box. To continue the exploratory analysis, we specify a set of factors that we presume contribute to the final loading level. Other researchers have attempted to specify such categories as land use or perhaps traffic density as intuitively plausible factors; we would expect industrial and commercial land to have patterns of accumulation that differ from low-density residential. Nevertheless, it may well be that other factors, including a generally high "residual" variability, may mask these effects. This was found to be the case in the URS study: high variability within categories -- as measured via t-tests -- hampered the attempt to distinguish differences in accumulation among land use categories. As we have seen, this is due in part to the use of raw data; log transformed values do not behave quite so badly. Another approach is to use medians instead of a least squares analysis because medians are insensitive to extreme fluctuations in the data. To perform the analysis, we disaggregate the data into a model of the form:

LOADING = common value (over all categories)
+ land use effect
+ traffic effect
+ climate effect
+ residual

where the residual is a normally distributed source of error. We are in effect making the categories into "dummy variables."[2]

Appendix A describes all the steps to be performed in applying this technique. The results are presented in Tables 5-2 to 5-5. The numbers left in the center cells are that part of the loading not accounted for by climate, land use, or overall value -- the residuals.

TABLE 5-2. TWO-WAY TABLE ANALYSIS, LOG MEDIAN SUSPENDED SOLIDS LOADING, LAND USE VS. CLIMATIC REGION, LBS/CURB-MILE/DAY (URS, 1974)

Original Data	Region				
Land Use	Northeast	Southeast	Northwest	Southwest	Row Median
residential	2.13	1.70	1.59	1.43	1.65
commercial	2.01	1.61	1.20	1.61	1.61
light industry	2.13	2.02	1.77	1.93	1.98
industry	2.71	1.64	1.59	1.87	1.76

The Two-Way Fit: Loading = Common Value+ Land Use (row) Effect + Region (column) Effect + Residual

					Row Effect
residential	0.01	-0.01	0.13	-0.25	-0.08
commercial	-0.01	0.01	-0.15	0.04	-0.18
light industry	-0.29	0.02	0.02	-0.04	0.22
industry	0.43	-0.22	-0.02	0.04	0.07
Column Effect	0.44	0.03	-0.23	-0.01	1.76 (common value)

---

[2] The classic statistical approach to fitting a linear regression model to observed data is to use a "least squares" criterion for the fit. If we displayed the data in categories (as in Tables A-1 and A-2) we could follow this technique by subtracting out the row and column means for each category, and by arriving at a formula such as

fit = grand mean + row effect + column effect + residual,

it can be formally shown that the linear decomposition in a model of this kind is equivalent to a least squares analysis. However, least squares is ineffective with highly variable data because, as the least squares derivation shows, points farther away from the grand mean ($\bar{X}$) contribute more to the placement of the least squares line than points closer to the mean (the exact factor is $\partial f(X_i - \bar{X})/\partial X$, where X_i is the particular observation and $\bar{X}$ the mean). But why should "untypical" points contribute more to the direction of the line? Shouldn't it rather be the "typical" points that determine the line? In the face of these arguments it has been suggested that the medians be subtracted out instead of the means, thus providing an inherently "typical" value, not one influenced by extreme values. This gives us Tables 5-2 and 5-3.

TABLE 5-3. TWO-WAY TABLE ANALYSIS, LOG MEDIAN SUSPENDED SOLIDS LOADING (LBS/CURB-MILE/DAY) CLIMATIC REGION VERSUS TRAFFIC DENSITY

Original Data	Traffic Density (ADT)				
Climate	<500	500-5000	5000-15000	>15000/day	
Northeast	2.55	2.08	2.16	2.32	
Southeast	1.76	1.83	1.66	1.23	
Southwest	1.15	1.72	1.41	1.55	
Northwest	absent	1.34	1.62	1.20	
The Two-Way Fit					Row effect
Northeast	0.12	0.27	-0.12	0.34	0.75
Southeast	-0.03	0.12	0.02	-0.11	0.11
Southwest	-0.47	0.12	-0.12	0.32	0
Northwest	absent	-0.23	0.12	0	-0.03
Column Effect	0.12	0.04	-0.03	-0.33	1.56 (common value)

The "common value" is an overall measure of the load. The "effects" are what they say they are -- in the case of land use and region, the effect of being in a particular land use or climatic category. For example, in Table 5-2 being in the Northeast adds 0.440 to the common value of 1.76; being residential adds -0.08 (the URS "overall" value is 156 (43.98) -- too high compared to the model above (anti-log 1.76 = 57.5)). Notice that this model is linear in a log scale, hence actually multiplicative.

The basic results are these:

land use versus climatic region; suspended solids loading (Table 5-2):

- Land use effects
  - Commercial areas are somewhat lower in loading rates; light industrial is somewhat higher. (There are few observations for the "light industry" category, so this latter result must be viewed with some caution).
- Climatic region effects
  - In general, climate has larger effects on loadings than does land use.
  - The Northeast has a substantial positive effect; the Northwest, a negative one. The other regions have almost negligible effect. One explanation is that the aged infrastructure in the Northeast contributes to increased loadings, whereas the long rainy periods (or different vegetation?) in the Northwest prevent large build-ups; however, these are just speculations, particularly since the relationship between loading and days since last rain is problematic.

- Residuals
  - There are large residuals for residential Southwest (-0.25), Northeast light industrial and industrial (-0.29, 0.43), and Southeast industrial (-0.22) -- as large as any land use or climate effects. These all suggest details unaccounted for by the gross categories of land use and climatic region, particularly for the Northeast. Are these local disturbances?
- The simple model does a better job than the URS classification method: the residential Northeast mean given by URS method is 291 (82.04), whereas the reported value is 197 (55.54). That is an error of 48 percent. The two-way table method predicts a median value of 132 (37.22) compared to an actual value of 135 (38.06) -- an error of two percent. Of course, in an area with large residuals, the Northeast, neither method can be expected to do well.
- Examination of residuals in a stem-and-leaf display (Figure 5-5) indicates that the median is 0, as it should be. The residuals look about normal with some high and low values as noted. A diagnostic plot of residuals versus (row effect x column effect)/ common value (Figure 5-6) is used to reveal any systematic trend in the residuals that would indicate an interaction between land use and climatic region. (The additive, linear form of the table assumes there is no such interaction; i.e., the effects of land use are independent of the effects of climatic region. The diagnostic plot is designed to test for the interaction) In this case there is no clear pattern to the residuals. However, we note the large residuals for industrial and light industrial northeast areas.

Traffic density versus climate, land use, and landscaping beyond the sidewalk, respectively, for solids loading (Figures 5-3, 5-4, 5-5)

- Traffic effect

  In general, in all three tables increasing traffic from the lowest to the highest category lowers the accumulation up to .3 to .5 log units. This effect is more notable for the traffic versus region fit. We assume that the result is due to scouring caused by larger volumes of traffic. (Figure 5-7 plots this effect versus traffic volume) To test this directly, least squares regressions of average daily traffic volume versus accumulation were calculated; however, in no case was the R^2 value greater than 0.15. It appears that the information is only sufficient to do analysis by categories of traffic volume, as in two-way tables.

- Climate, land use, and landscaping effects

  For climatic regions the Northeast has a sizeable positive effect apparently due to commercial areas being substantially lower (street sweeping); landscaping matters very little.

TABLE 5-4. TWO-WAY FIT, LOG (AVERAGE DAILY MEDIAN SUSPENDED SOLIDS) (LBS/CURB-MILE/DAY) LAND USE VS. TRAFFIC VOLUME (ADT) (URS, 1974)

Original Data

Land Use	Traffic Volume less than 500	500-5000	5000-15000	greater than 15000	row median
Residential	2.18	2.08	1.73	1.98	2.030
Commercial	absent	1.49	1.46	1.40	1.460
All Industrial	2.44	2.09	1.94	1.26	2.015

The Fit

Land Use	Traffic Volume less than 500	500-5000	5000-15000	greater than 15000	row median
Residential	-0.097	0.057	-0.143	0.079	0
Commercial	absent	-0.032	0.088	0.000	-0.501
Industrial	0.096	0.000	0.000	0.678	0.067
column effect	0.321	0.067	-0.083	-0.055	1.956 (common value)

```
Residuals x .100
       |
   2   |
   1   |
   .   |5789
 0**   |000
   -   |39
  -1   |4
   .   |
  -2   |
   .   |
 -3**  |
   .   |
  -4   |                  upper hinge = 0.06
   .   |     n = 11            median = 0.00
 -5**  |                  lower hinge = 0.06
   .   |
  -6   |
   .   |7
 -7**  |
       |
```

TABLE 5-5. TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS LOADING, LBS/CURB-MILE/DAY) LANDSCAPING VS. TRAFFIC DENSITY (ADT) (URS, 1974)

Original Data	Landscaping				
Traffic Volume	grass	trees	landscaped buildings	none	row median
less than 500	2.217	absent	1.900	absent	2.059
500-5000	1.863	1.505	2.170	1.968	1.916
5000-15000	1.613	1.544	1.663	1.778	1.638
> 15000	1.230	1.982	0.062	1.301	1.266

The Fit	Landscaping				
Traffic Volume	grass	trees	landscaped buildings	none	row median
less than 500	0.143	absent	-0.093	absent	+0.313
500-5000	-0.008	-0.259	0.380	0.000	0.110
5000-15000	-0.038	0.000	0.093	0.030	-0.110
> 15000	0.009	0.868	-0.538	-0.017	-0.540
column effect	0.015	0.092	0.066	-0.017	1.746 (common value)

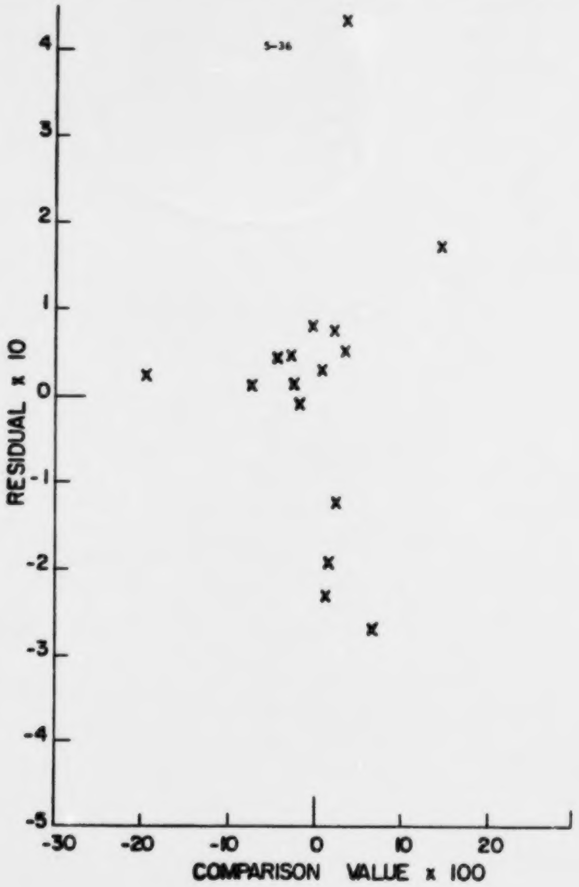
Residuals x 0.001

```
 8** | 6
   6 |
 4** | 8
   2 | 4
  +0 | 00930
  -0 | 9031
 -2** | 5        n = 14    upper hinge = 0.093
  -4 |                          median = 0.000
     | 3                   lower hinge = 0.038
 -6** |
```

FIGURE 5-5. RESIDUALS FROM TWO-WAY FIT OF LAND USE VS. CLIMATIC REGION

```
Residuals x 100
     4 | 3
     3 |
     2 |
     1 | 3
    +0 | 004224
    -0 | 0042
    -1 | 5
    -2 | 592
    -3 |
    -4 |
  median = 0.0
```

FIGURE 5-6. DIAGNOSTIC PLOT, RESIDUALS FROM TWO-WAY FIT LOG (SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LAND USE VS. CLIMATIC REGION



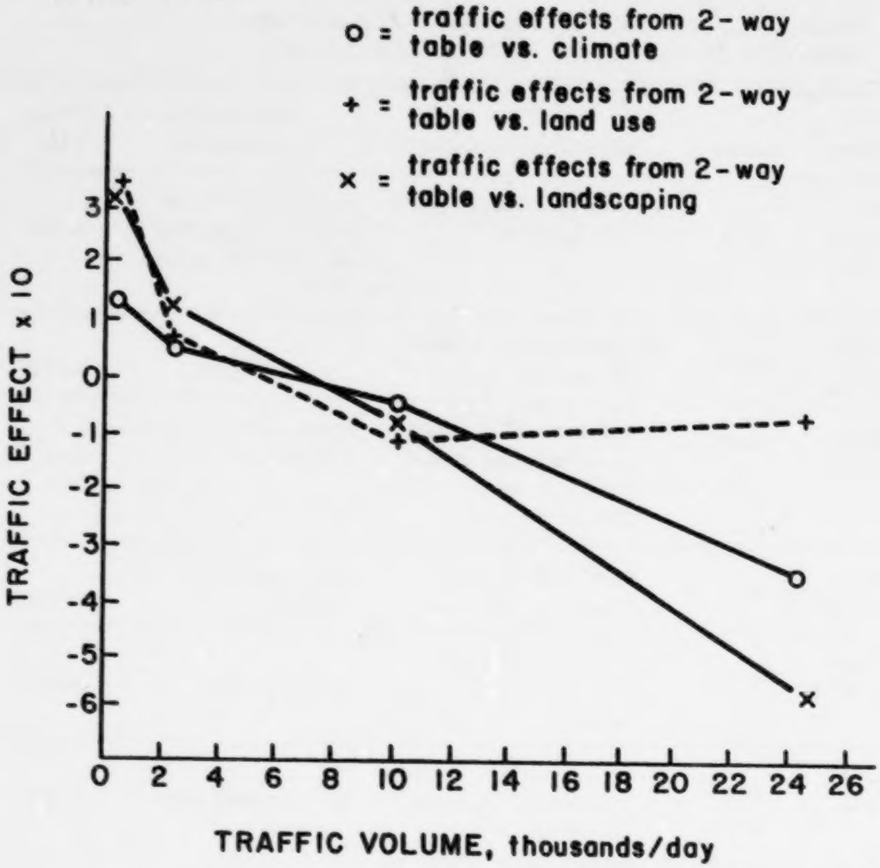


FIGURE 5-7. TRAFFIC EFFECTS VS. TRAFFIC VOLUME

- Residuals
  - There are large residuals remaining even after traffic and climate, land use, or landscaping effects are subtracted out. This indicates substantial "unexplained" variation remaining in some categories, though in some cases (e.g., traffic versus land use) this is likely because of the small number of sample values in a category. Residual plots are given following the tables which show generally random scatter, indicating proper linear disaggregation of the row and column effects.

Instead of an in-depth discussion of other two-way tables, a summary of the results is given in Table 5-6. The reader can refer to the tables and diagnostic plots in Appendix A for details.

Briefly, we can see that:

- the northeast and southwest regions fluctuate -- either with positive or negative effects -- more than any other climatic region. Generally the Southwest has moderately higher loadings.

TABLE 5-6. SUMMARY OF TWO-WAY TABLE RESULTS
(ANALYSIS BY LOG OR LN (MEDIAN CONSTITUENT))

Material	Effect	Table #	Effects: Comments	Residuals: Comments	Diag. Plot
Solids	LS* Climatic Region	A-5.	"trees" much lower NE* higher	interaction between climate/ LS beyond sidewalk	A-15
COD	Land Use LS	A-6	commercial lower LS little effect	interaction	A-16
COD	Climate Land Use	A-7	industrial lower residential-commercial same SW* higher	some large residuals	A-17
Lead	Traffic Land Use	A-8	traffic effect clear	some interaction	A-18
Lead	Land Use Climate	A-9	industrial lower NE* lower, SW higher	interaction	A-19
Lead	Land Use Traffic	A-10	scouring at high volumes; deposit at other volumes commercial much higher	no interaction	A-20

*LS = Landscaping; NE = Northeast; SW = Southwest

- residential land uses do not contribute much to loadings, but industrial and commercial uses do have some sizeable effects. Lead and COD are higher in commercial areas; lower in industrial areas. Solids are lower in commercial areas; higher in industrial areas.
  - It is interesting that the lead and COD land use effects are different in sign from the solids land use effects. This suggests that solids deposition differs perhaps significantly from those processes that specifically accumulate COD or lead. The implication is that models that rely on solids accumula-estimates alone cannot be expected to do a reasonable job of estimating particular pollutants like BOD or metals that do not deposit or erode as solids do.

- lead deposition by traffic follows an intuitively satisfying pattern: deposit at low-medium volumes; scouring at highest volumes.
- There are interactions between land use, climate, and landscaping for the majority of the tables. In the case of landscaping this interaction is possibly the result of association between vegetation types and climate types -- for example, more trees in the Northeast.

ANALYSIS OF SAN JOSE STREET CLEANING DATA

One of the most recent studies of street surface accumulation is that done in San Jose, California by Woodward-Clyde Consultants in 1977. Importantly, this report contains a series of before-cleaning/after-cleaning samples done in the same locations under carefully controlled conditions. The number of samples taken was based on an initial estimate of the variability of the loading to establish a uniform confidence estimate for the figures obtained. The reporting is particularly complete, giving particle size distributions (in percentage of total and absolute amount) for each sample. This is useful, since some models (for example, that of Sutherland and McCuen, 1976) posit washoff varying with particle size. Further, the proportion of particular contaminants (e.g., BOD) seem to vary with particle size (See Table 5-7).

Validation of the Accumulation Model

The San Jose data can be used to test the validity of the accumulation model presented above. There we stated that solids accumulation could be fitted as:

load = overall load + row effect + column effect + residual

where "row effect" and "column effect" correspond to our knowledge of, for example, what land use and climate category the chosen site is in, and "residual" is a randomly distributed remaining error.

TABLE 5-7. FRACTION OF POLLUTANT ASSOCIATED WITH EACH PARTICLE SIZE RANGE (% BY WEIGHT)*

	MICRONS					
	>2000	840-2000	246-840	104-246	43-104	>43
Total Solids	24.4	7.6	24.6	27.8	9.7	5.9
Volatile Solids	11.0	17.4	12.0	16.1	17.9	25.6
BOD_5	7.4	20.1	15.7	15.2	17.3	24.3
COD	2.4	4.5	13.0	12.4	45.0	22.7
Kjeldahl Nitrogen	9.9	11.6	20.0	20.2	79.6	18.7
Nitrates	8.6	6.5	7.9	16.7	26.4	31.9
Phosphates	0	0.9	6.9	6.4	29.6	56.2

*Source: Sartor, J.D., and G.B. Boyd, Water Pollution Aspects of Street Surface Contaminants, Report prepared for U.S. EPA, EPA-R2-72-081, Washington, D.C., 1972.

If we take a fixed street location in the San Jose test area ("Tropicana" Street), we can presumably fix the row and column effects; we further control for possible effects of accumulation time by looking only at a single day following a street cleaning. Therefore, the remaining observed variation in accumulation should be due solely to what we have termed "residual error." If we plot these residual loading rates in a stem-and-leaf (Figure 5-8 for particles less than 600 microns), we see that there is a large remaining variation (median = 44 lbs (12.3 Kg) spread = 57 lbs (15.9 Kg)). Even with presumably all effects of location and time of accumulation taken into account, the remaining spread of loads is quite large. In particular, there are several occasions when measured load on the street is lower the day after a sweep (negative loading rates in the figure). This surprising result could be caused by wind or traffic scouring; it is quite large in some instances. Further, the distribution is roughly of the shape expected by our model.

If we look now at the larger particles in a so-called box-and-whiskers plot (see Figure 5-9, particles greater than 600 microns), we find generally lower loading rates (median 19 (15.32)) and less variation. In the figure the upper and lower "tails" represent the maximum and minimum data values. Between them is a rectangular box whose top is the upper hinge and whose bottom is the lower hinge of the data. The line inside the box is the median value. One can see that the display is designed to give a quick visual idea of the spread of the data, since about 50 percent of the data values lie inside the box. If the data are not symmetric, the median is likewise not centered in its box. We suspect the cause to be that larger particles are less susceptible to variation caused by wind or traffic, hence have a "tighter" distribution. If we study the size distribution of particles, we see that cleaning removes a disproportionate share of large particles in part by grinding the larger particles into smaller ones.

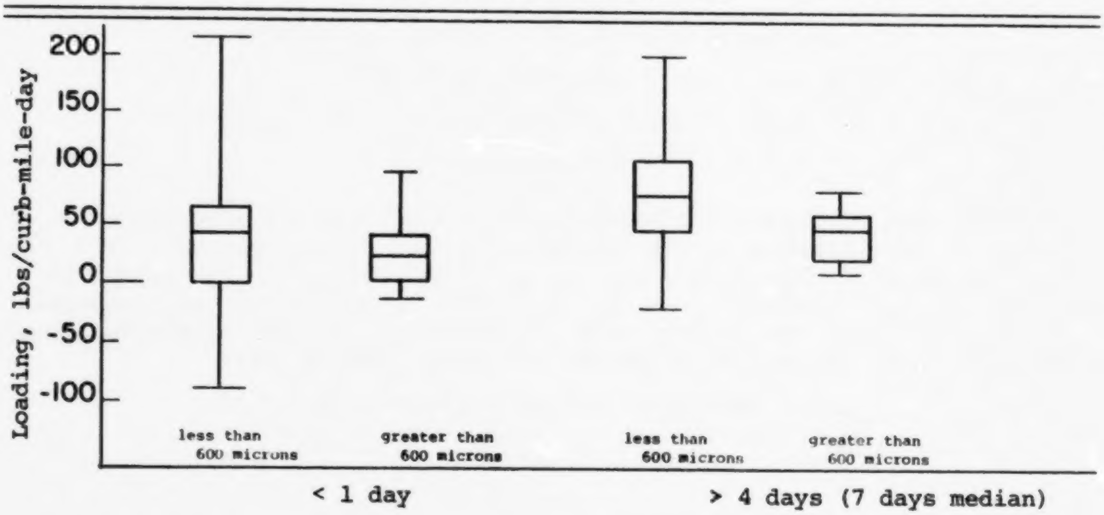
Clearly the inability of the sweepers to pick up smaller particles also plays a role in these effects. There are several other cases in the San Jose data where the day following a cleaning shows an increased rate of large particle deposition relative to small sizes; this makes sense if one looks at a simple rate equation by particle class -- there is more room for increase in the large particle class if the sweeper has differentially removed material from that class.

What of the effects of days of accumulation before a street cleaning? Figure 5-9 compares the distribution of loadings after one day and after four or more days of accumulation. The figure tells us that the substantial variation in loadings found in the smaller particle size range for less than one day accumulation is also present in the four- or more-day loadings (median seven days). Likewise, the smaller variability in the loading of larger particles is found even after four days of accumulation. Comparing the median load after one and after seven days, we see that for particles less than 600 microns, after less than one day loads have reached 68 percent of their seven-day value; the corresponding figure for larger particles is 59 percent. For the generally used exponential accumulation model, $L = L_o(1-e^{-kt})$, the first result implies a "k" value of 1.14, which means that 90 percent of the ultimate load is attained after only about two days. The conclusion is an important one for certain control measures such as street sweeping; for example, in order to reduce the average material available for washoff to 50 percent of its maximum value, one would have to sweep at intervals of under two days.

FIGURE 5-8. TROPICANA STREET LOADING RATES, LBS/CURB-MILE-DAY (PARTICLE SIZE LESS THAN 600 MICRONS)

```
(219,204)            unit = lbs                 15 | 2
  15 |                                          14 |
  14 | 9                                        13 |
  13 |                                          12 | 9
  12 |                                          11 |
  11 |                                          10 | 5
  10 |                                           9 | 6
   9 |                                           8 | 635
   8 | 4                                         7 | 7
   7 | 8                                         6 | 05
   6 | 00                                        5 | 911
   5 | 4333                                      4 | 2
   4 | 4     No. Observations = 23               3 | 1   No. Observa-
   3 | 169                                       2 |         tions = 17
   2 |                                           1 | 4
   1 | 8          60 = upper hinge = 96          0 |
   0 | 24303      44 = median      = 65         -1 |
  -1 |             3 = lower hinge = 42         -2 |
  -2 |                                          -3 | 5
  -3 | 3                                        -4 |
  -4 |    less than 1 day        greater than 4 days
  -5 | 2  accumulation                accumulation
```

FIGURE 5-9. LOADING RATES VS. DAY SINCE LAST RAIN OR SWEPT, TROPICANA STREET AREA, SAN JOSE, 1977



A second important conclusion to draw from Figure 5-9 concerns the large variability of loadings. Any control measures must consider that after only one day in the Tropicana Street location, one-half of the small particles loadings were between 60 and 3 lbs/curb-mile (16.80 and 0.84 kg/curb-km); after 7 days the spread is 54 (15.12). Therefore, the efficacy of any control program is subject to wind fluctuations; it appears that perhaps due to wind and traffic, street cleaning is inherently an uncertain kind of control, one that is not robust. What this means is that in order to achieve a virtually certain level of pollutant reduction on the street (for example, 90 percent sure), it would be necessary to raise the median cleaning level to possibly even a daily regime.

Mathematical Modeling of the Accumulation Data--

The basic loading rate equation is:

$$\frac{dL}{dt} = k_1 - k_2 L \qquad (5\text{-}1)$$

where k_1 = accumulation constant

k_2 = erosion constant

L = loading

t = time

If k_1 and k_2 are generalized, we obtain:

$$dL/dt = f(t) - f(L) + \text{random component} \qquad (5\text{-}2)$$

Suppose the deposition is non-linear, say $a/(1+bt)^2$, so that possible deposition diminishes with time. There is no analytic solution to this differential equation (there is an integral equation solution), but a series solution expanded to two terms gives

$$\begin{aligned} L = -a/(1+bt) &+ ac/b^2(\ln(1+bt) \exp - (ct)) \\ &+ c(1+bt) \exp - (ct) \\ &+ c^2(1+bt)^2 \exp - (ct) \\ &+ (a/b+c+c^2/4). \qquad (5\text{-}3) \end{aligned}$$

The load approaches its asymptotic value quickly for a selection of a, b, and c, corresponding to the "standard" differential equation (5-1). Figure 5-10 shows a graph with some typical a, b, c values -- the asymptotic limits are just fictional. It can be quickly seen that this more general equation can cover the simpler case, equation 5-1, as well as the empirically derived curves of Sutherland and McCuen (1976), Figure 5-11:

$$\text{load (industrial)} = 1388(1 - \exp(-.19t))$$
$$\text{load (commercial)} = 500(1 - \exp(-.535t))$$
$$\text{load (residential)} = 1089t(1+1.3t)).$$

FIGURE 5-10. ACCUMULATION LOAD VS. TIME; "COMPLEX" DIFFERENTIAL EQUATION

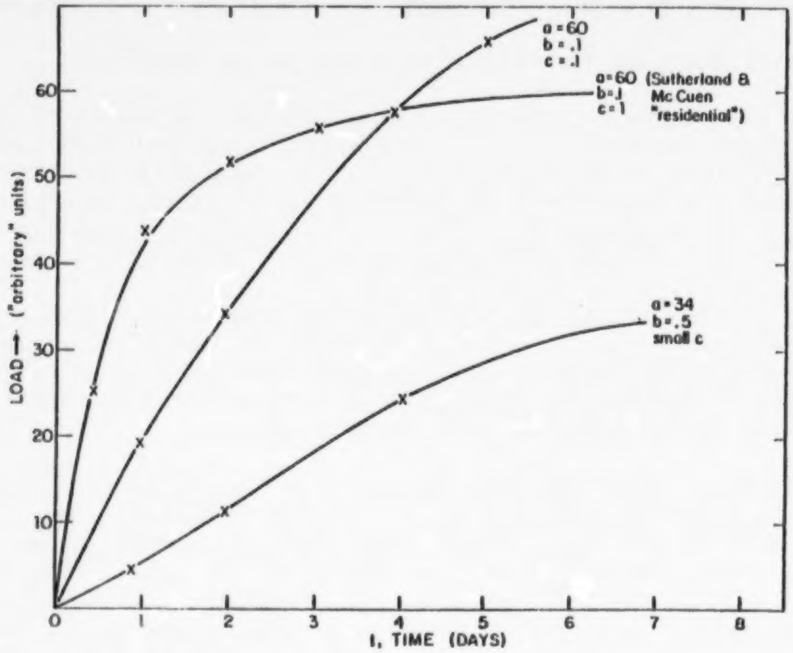
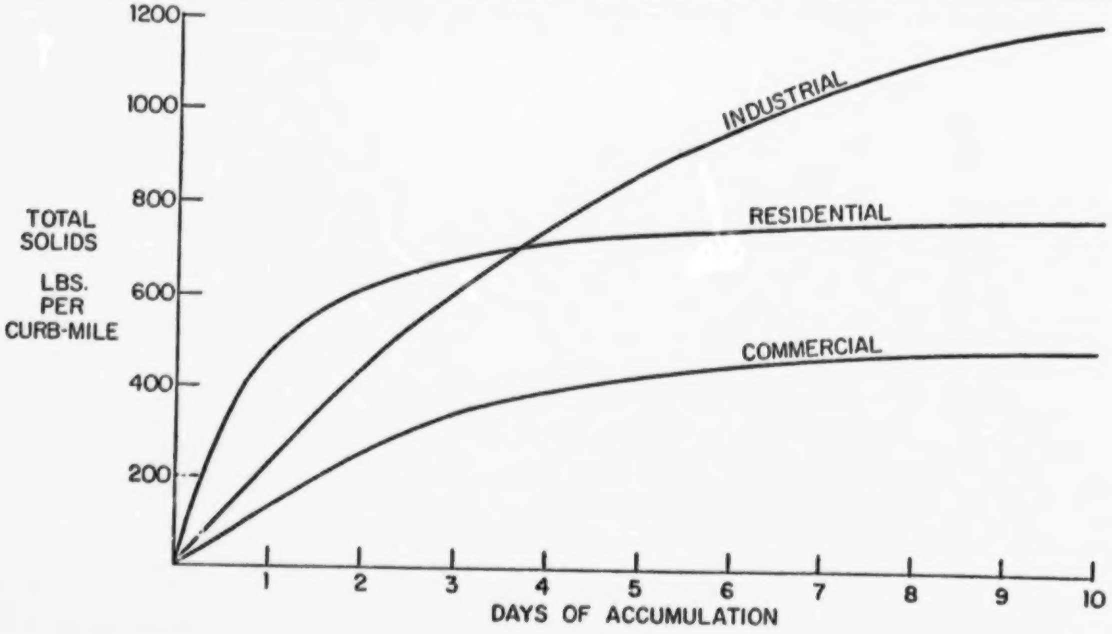


FIGURE 5-11. SUTHERLAND AND McCUEN EMPIRICAL CURVES



Further, as is shown in the analysis of the San Jose street cleaning data, the fast rise time to a saturation level after two to three days is generally confirmed by data from the "Tropicana" and "Keyes" Streets test sites.

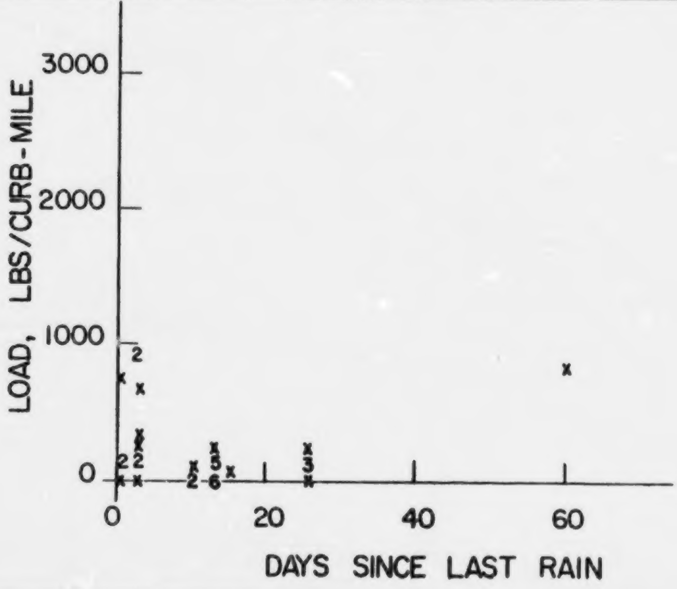
The Confusion About Estimated Days of Accumulation (EDA)--

Given that the simplest differential equation for loading is of the form load = function (time since last washoff), it is natural that investigators have tried to confirm this empirically. There have been contradictory results. Colston, Hammer, URS, and Whipple, among others, found no relationship between EDA -- number of days since last washoff -- and the loading. On the other hand, Sutherland and McCuen (1976) reported the opposite.

Least squares regressions of solids and lead versus "days since last rain" using the URS data gave extremely small R^2 values (less than 0.1). It is concluded that not much of the observed variation in loading is due to the accumulation as measured in days. See also Figure 5-12 (this pattern corresponds closely to the form found by Whipple, 1977).

In the case of the URS data the negative finding is not surprising, since most samples of different EDA's are from different cities: Baltimore, with nine data points, all 26 days after the last washoff; Atlanta, all 2 days, and so on. Within one city there are few different EDA's; thus to expect the EDA to account for loading differences between cities is to believe all the data to be from one "city," but this is not the case. Further, the San Jose data show a rise time in one to three days to a loading "saturation." To capture this fluctuation, sampling would have to be done at intervals much shorter than a single day; that is, hours.

FIGURE 5-12. LOADING VS. DAYS SINCE LAST RAIN (URS, 1974)



Conclusions

Implications for Modeling Accumulation--

	Observations		Modeling Implication
1)	fast rise time to saturated loading	1)	use non-linear accumulation equation
2)	deposition and pollutant composition varies with particle size	2)	disaggregate deposition depending on severity of variation
3)	a. large variability in error term of statistical estimate of load; b. production of small particles by street cleaning	3)	incorporate variance estimate into effectiveness of control measures like street cleaning
4)	conflicting reported effects of "days of accumulation"	4)	smaller sampling intervals (less than 1-2 days) required only if necessary to capture the effect of accumulation time

ANALYSIS OF WASHOFF: THE ENVIREX-DOT DATA

To study the changes in pollutant concentrations at different stages of storm runoff flow, it is necessary to find data that: 1) measure different pollutant parameters over the evolution of storm; and 2) measure storm runoff independently of stream flow and sanitary sewer flow. Such data have been collected in a recent study by the Envirex Corporation for the Department of Transportation, and that portion of the data released in time for evaluation in this study (i.e., 12 rainfall events in 3 different catchments) is the basis of this section of our report. Table 5-8 displays some relevant characteristics of these catchments.

TABLE 5-8. DOT CATCHMENT DESCRIPTION

Catchment	No. Rainfall Events	Runoff Area	ADT*	Description of Area
Harrisburg Catchment	7	18.5 acres	24000	paved/unpaved
Milwaukee Catchment A (Highway 45)	4	106 acres	85000	31% impervious
Milwaukee Catchment B (Highway 794)	1	2.1 acres	52000	completely impervious

*Average Daily Traffic Volume.

The DOT data include observations of precipitation, flow, suspended solids, total organic carbon, and pH for each storm. Most storms have observations of other parameters, including Cd, Cu, Cr; Fe, Pb, Cl^-, NO_2, NO_3, TKN, PO_4, BOD_5, COD, and oil and grease.

Regression analysis was used to search for equations which appear to explain the level of pollutants as a function of runoff flow volume. The analysis focused on the suspended solids parameter in recognition of its general physical properties and the relatively complete information available, but other parameters were examined as well. Analysis was undertaken for individual storms, for aggregates of storms in each catchment, and for an aggregate of data over all catchments.

In the analysis of individual storms the relationship of suspended solids to flow was studied by comparing cumulative suspended solids to cumulative flow. Figures 5-13 and 5-14 show this relationship for each storm. Simple observation of these plots suggest that 1) a first flush effect is found in each storm, and 2) cumulative suspended solids decay exponentially relative to cumulative flow. (See Appendix A for a discussion of the technique used to develop data for these studies.)

FIGURE 5-13. CUMULATIVE SUSPENDED SOLIDS VS. CUMULATIVE FLOW FOR HARRISBURG STORMS

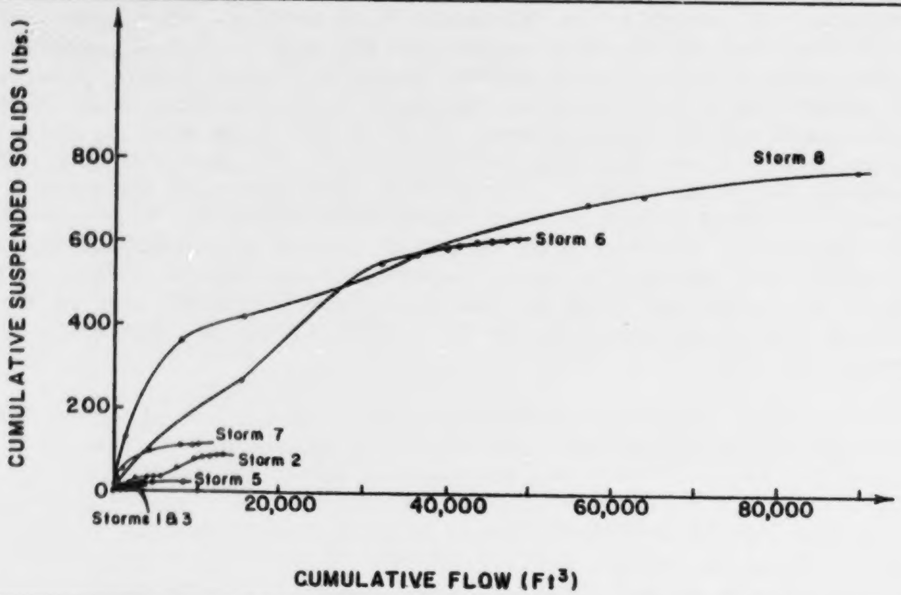
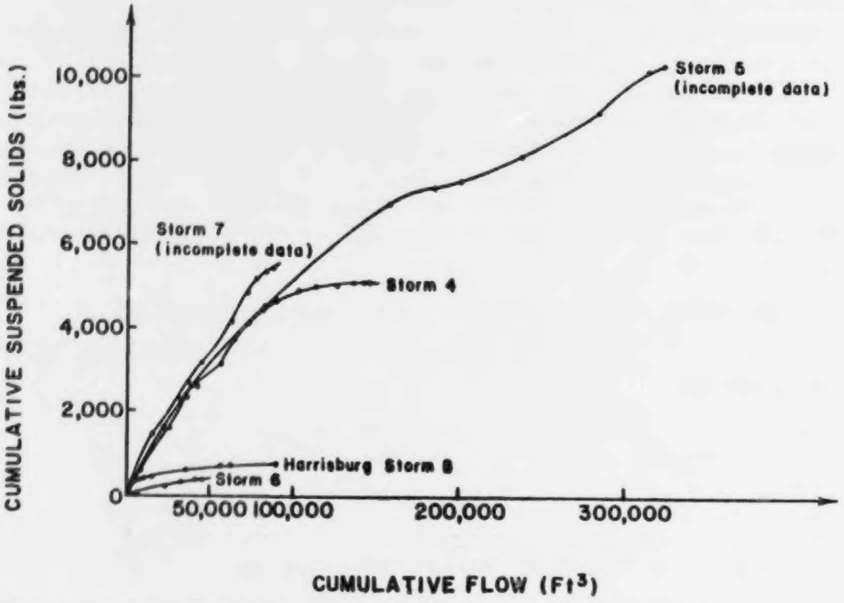


FIGURE 5-14. CUMULATIVE SUSPENDED SOLIDS VS. CUMULATIVE FLOW FOR MILWAUKEE STORMS (INCLUDING THE HARRISBURG STORMS)



Cumulative Plots of the Harrisburg Storms

Figure 5-13 suggests the existence of an envelope or a characteristic shape of suspended solids-flow curves whereby storms of a threshold intensity will rise along a common slope before diverging toward their individual horizontal asymptotes. The Milwaukee catchment A plot (Figure 5-14) also shows this, although two of these storms, events 5 and 7, are missing data in the latter portions of the flow and consequently do not show the decay effect observed in the other storms. Figure 5-14 also serves to contrast a characteristic Harrisburg runoff pattern (Harrisburg Storm #8) to the Milwaukee storms, indicating the degree of variation in the suspended solids-flow relationship that may be due to differences in catchments. This last observation is partially explained by the difference in runoff area of the two catchments (the Harrisburg site is 18.5 acres (7.40 ha), while the Milwaukee catchment A is 106 acres (42.9 ha)).

Some summary results of the regression analysis are shown in Table 5-9. Complete fitted equations are only shown for Harrisburg storms 7 and 2, but R^2 values for the different regressions are shown for each storm. The two Harrisburg storms were chosen to represent a range of different types of storm that can be described by the same regression models (#7 had a single peak flow, while #2 had two periods of high flow). While the curves representing the storms differ greatly (see Figures 5-15 and 5-16), the regression coefficients and residuals are different -- both storms exhibit high R^2 values for several of the fitted models. In other words, while there is unexplained variation between storms, the within-storm variation is explained rather well by bivariate regression models.

Generally, the most successful model was of the form suspended solids = Lo (1-exp (flow*k)), where suspended solids (lbs) and flow (ft^3) are cumulative, Lo is a constant representing the potential total amount of suspended solids that could be washed off, and k is an empirically derived constant. This so-called "exponential" model is related to the functional form used by the SWMM computer program (see discussion below). Coefficients for the model were found using non-linear regression techniques, but a variation of the "method of moments," developed by Moore, Thomas, and Snow (1950) for analyzing BOD data can be employed as a manual tool for deriving the model coefficients.

TABLE 5-9. REGRESSION FITS FOR HARRISBURG STORMS

Harrisburg Storm No. 7	
$ss = -55.89 + 40.49 * \log_{10}(flow)$	$R^2 = .889$
$ss = -15.22 + 6.68 * flow^{(.326)}$	$R^2 = .989$
$ss = 111.00 * (1. -\exp(-flow * .000563))$	$R^2 = .995$

Note: ss is cumulative suspended solids and flow is cumulative flow.

TABLE 5-9 (CONTINUED)

Harrisburg Storm No. 2

$ss = -205.16 + 69.1 * \log_{10}(flow)$ $R^2 = .865$

$ss = -15.22 + 6.68 * flow^{(.909)}$ $R^2 = .968$

$ss = 163.19 * (1. -\exp(flow * .000059))$ $R^2 = .964$

All Storms -- R^2 values

	H1	H2	H3	H5	H6	H7	H8	MA5	MA6	MA7	MA8	MB1
Linear-log model	.980	.865	.982	.562	.912	.884	.973	.788	.770	.961	.760	.988
Non-linear model	.983	.968	.988	.902	.987	.989	.997	.977	.997	.995	.999	.994
Exponential model	.976	.964	.995	.910	.993	.995	.961	.995	.994	.991	.997	.994

Note: ss is cumulative suspended solids and flow is cumulative flow.
ss = pounds
flow = cubic feet

FIGURE 5-15. CUMULATIVE SUSPENDED SOLIDS VS. CUMULATIVE FLOW
HARRISBURG STORM #7

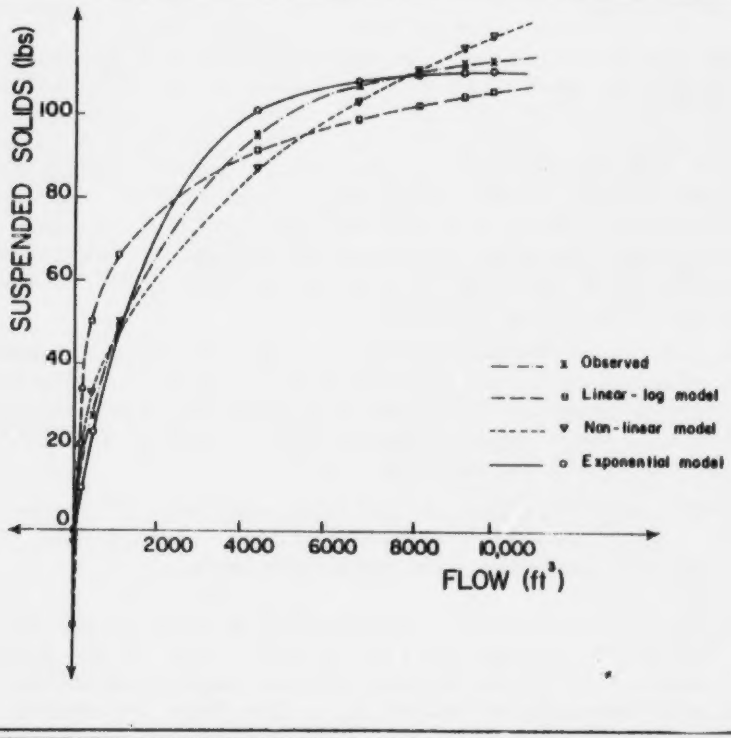
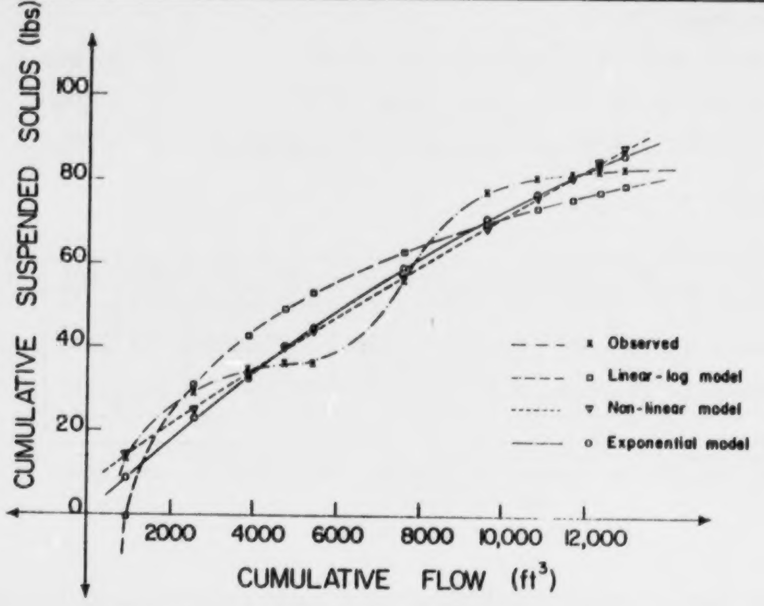


FIGURE 5-16. CUMULATIVE SUSPENDED SOLIDS VS. CUMULATIVE FLOW HARRISBURG STORM #2



Examination of Residuals

Even though the R^2 values for the exponential model are quite good, it is worthwhile to examine where the fitted values differ from those observed. Figures 5-17 and 5-18 display the residuals remaining in the Harrisburg Storms #7 and #2 after an exponential fit. Both fits show observable trends in the residuals, indicating that the exponential model consistently overpredicts suspended solids in the early portions of storms. Harrisburg Storm #2, in particular, shows a sinusoidal pattern of residuals: the model does well in predicting the middle portion of the storm, but not the beginning or end (Figures 5-15 and 5-16 also tell the same story). There are several conclusions that might be drawn:

1) Even though the R^2 values (the overall fits) are quite good, this is misleading. If one is interested in predicting first flush effects or total final solids, then the actual fit is not quite so good. The implications for computer modeling of storm events is discussed below.

2) The unexplained variation in the early sections of storms suggests a more complicated relationship between solids washed off and flow than that presented here.

3) The analysis of residuals is recognized as limited by the data. All of the storms had more observations in the later (higher cumulative flow) portion because measurements were divided into equal time, rather than flow time increments.

FIGURE 5-17. RESIDUALS FROM FIT, HARRISBURG STORM #7

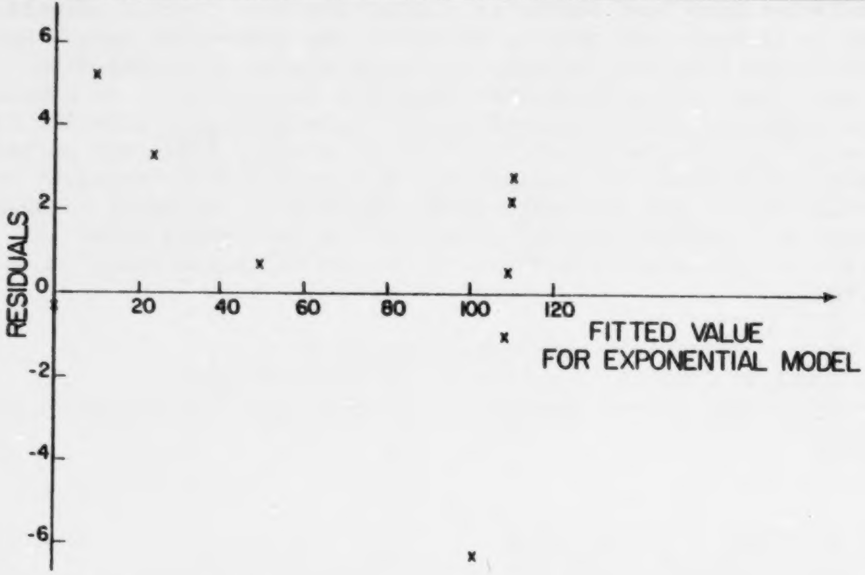
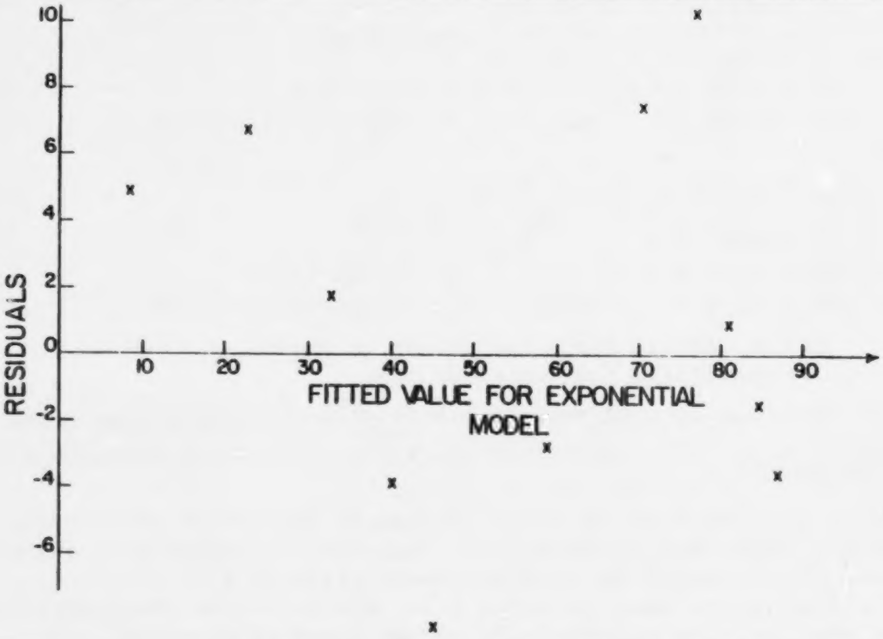


FIGURE 5-18. RESIDUALS FROM FIT, HARRISBURG STORM #2



When the data were aggregated within a catchment the level of explained variation was less exceptional, but still rather high, as shown in Table 5-10. The simple cumulative flow term serves as a proxy for more complex effects in each storm, but it is much less able to do so for the aggregated data. Exploratory correlations were made between suspended solids and total flow, average flow, peak flow, and mean squared flow (see Table 5-10). An examination of average suspended solids concentration versus peak precipitation (see Figure 5-19) showed some degree of correlation and visibly different patterns for the different catchments. By including a mean square flow intensity term in the exponential models for aggregate data regressions, the level of unexplained variation was reduced: the R^2 value for the Harrisburg model increased from .933 to .972 while the R^2 value for the Milwaukee model increased from .965 to .968.

TABLE 5-10. REGRESSION ANALYSES
CUMULATIVE SUSPENDED SOLIDS VS. CUMULATIVE FLOW

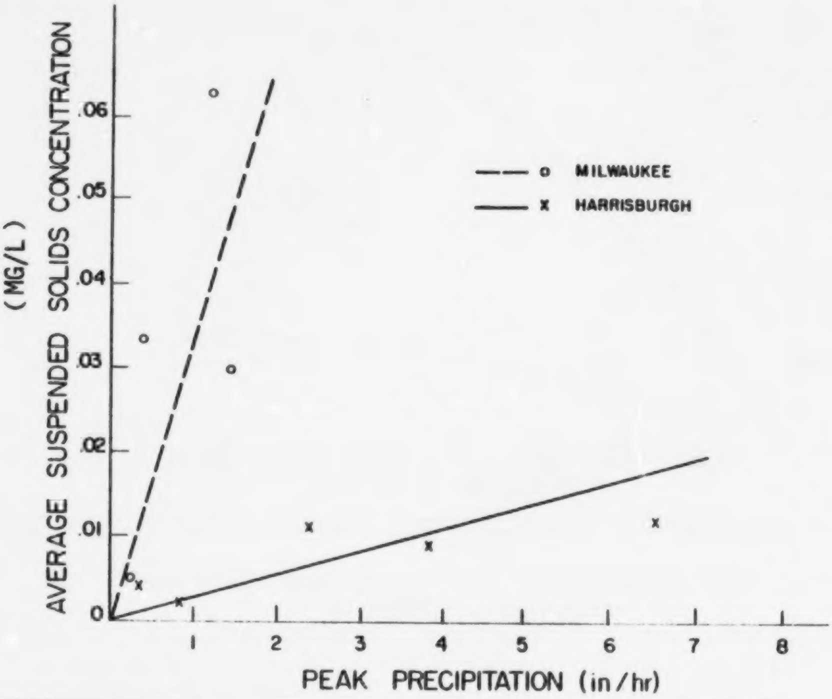
Aggregate Models		
Harrisburg (63)*	$ss = 9.61 + .0118 * flow$	$R^2 = .900$
	$ss = -534.826 + 195.79 * \log_{10}(flow)$	.515
	$ss = -32.60 + .202 * flow$	.919
	$ss = 1157.23 * (1 - \exp(-flow * 1.554\ E{-5}))$	.933
	$ss = 984.316 * (1 - \exp(-flow * 1.23\ E{-5})) + 8.50 * MS$	.972
Milwaukee A (48)*	$ss = 900.169 + .033 * flow$	.914
	$ss = -8131.91 + 2646.84 * \log_{10}(flow)$	.739
	$ss = -355.347 + 6.440 * flow$	.976
	$ss = 11066.5 * (1 - \exp(-flow * 6.086\ E{-6}))$	.965
	$ss = 10507.8 * (1 - \exp(-flow * 6.29\ E{-6})) + 1.826 * MS$	.968
All Storms (124)*	$ss = 76.996 + .0366 * flow$	.895
	$ss = -5677.6 + 1833.94 * \log_{10}(flow)$	.508
	$ss = -247.37 + .531 * flow$	.912
	$ss = 16819.8 * (1 - \exp(-flow * 2.939\ E{-6}))$	.915
	$ss = 15179.8 * (1 - \exp(-flow * 3.13\ E{-6})) + 2.944 * MS$	.919

ss = cumulative suspended solids in pounds
flow = cumulative flow in cubic feet
MS = mean squared flow in $\left(\frac{\text{cubic feet}}{\text{min}}\right)^2$ averaged over storm

*Number of observations.

Aggregating the data from all these catchments introduced another element of variation, which was expected after observing the distinctly different solids-flow relationships for each catchment (Figures 5-13 and 5-18). The regression results are shown in Table 5-10, and while the relatively high R^2 suggests a good fit, the substantially larger flows in Milwaukee catchment A have allowed that data to dominate the regression.

FIGURE 5-19. SUSPENDED SOLIDS VS. RAINFALL INTENSITY, MILWAUKEE AND HARRISBURG STORMS



Other Parameters

Similar analyses were performed for other pollutant parameters, though less extensive data limited aggregation or comparisons between storms. Figure 5-20 shows selected results for Milwaukee Event Number 4 and shows that all forms of suspended solids measured have constant or decreasing concentration with increasing flow (See Appendix A, Figures A-21 and A-22 for the remaining plots.) Milwaukee Storm #4 showed a similarity of non-linear regression coefficients as suspended solids, Fe, Cu, Cr, Pb, and Zn all fitted exponents between .43 and .53 (see Table 5-11). (A representative plot of zinc versus flow for Harrisburg Storm #7 is given in Appendix A, Figure A-23.) The similarity of the decay coefficients for different constituents suggests that all of these heavy metals behave alike in their washoff and deposition characteristics. If so, it may be possible with more extensive data to develop a single equation (perhaps based on particle size (see Pisano, 1977)) to account for observed amounts of all these metals. In contrast, total solids and chlorides show increasing concentrations with increasing flow; in this particular storm this is probably the result of snowmelt.

FIGURE 5-20. CUMULATIVE VSS, SS MILWAUKEE STORM #4

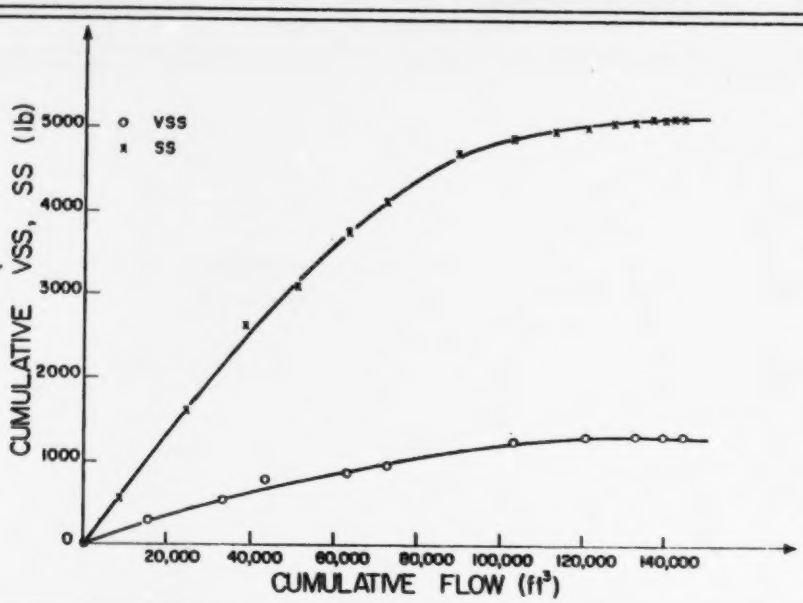


TABLE 5-11. NON-LINEAR MODELS FOR VARIOUS POLLUTION PARAMETERS
MILWAUKEE A, STORM #4

SS	$= -413.19 + 16.494 * \text{flow}^{.4945}$	$R^2 = .990$
TOC	$= -34.58 + 1.355 * \text{flow}^{.5034}$	$= .989$
Cu	$= -.0919 + .00525 * \text{flow}^{.485}$	$= .996$
Cd	$= -8.937\ \text{E-4} + 1.591\ \text{E-5} * \text{flow}^{.821}$	$= .998$
Cr	$= -.0271 + .00183 * \text{flow}^{.4699}$	$= .993$
Fe	$= -11.786 + .8180 * \text{flow}^{.4547}$	$= .990$
Zn	$= -.2956 + .01394 * \text{flow}^{.5319}$	$= .997$
Pb	$= -1.088 + .0932 * \text{flow}^{.4331}$	$= .993$
NO_2^-	$= .0276 + 1.395\ \text{E-5} * \text{flow}^{.9315}$	$= .999$
TKN	$= .0624 + 2.613\ \text{E-5} * \text{flow}^{1.0984}$	$= .990$
PO_4^{-3}	$= 1.261\ \text{E-4} + 4.781\ \text{E-4} * \text{flow}^{.7229}$	$= .997$
NO_3	$= .111 + 3.798\ \text{E-7} * \text{flow}^{1.3738}$	$= .998$
VSS	$= -63.632 + 2.457 * \text{flow}^{.5377}$	$= .987$

-- E-n is equivalent to 10^{-n}
-- Dependent variables in pounds
-- Flow in ft^3

Conclusions: Suspended Solids Fits

1) Cumulative flow accounts for a high proportion -- about 90 percent -- of the variation in suspended solids loading.
2) However, the pattern of consistent over- and under-prediction with increasing flow suggests remaining variation in solids levels that must be explained by a more complex model.

IMPLICATIONS FOR STORMWATER MODELING

All of the attempts at regression analysis above (and related work by Espey and Huston Associates, 1976) are in a sense simple formulations of proxy models of suspended solids washoff. While it may be objected that these functional forms predicting solids are not complex, they are like those used in the state-of-the-art computer models STORM and SWMM. It is therefore relevant to verify these functions and to examine the assumptions they embody.

STORM and SWMM both employ an exponential decay washoff function for impervious areas: change in $L = Lo\ (1 - \exp(kr_1t_1)) - Lo(1 - \exp(-kr_2t_2))$ (time 1 to time 2)

where Lo = ultimate loading (potential maximum)

r_1 = runoff inches/hour, time period 1

r_2 = runoff inches/hour, time period 2

t_1 = elapsed time from storm start, time 1 (hours or fractions of hours)

t_2 = elapsed time from storm start, time 2

k = decay constant (= default values 4.6 in SWMM, 2 in STORM)

L = washoff

To test this model, data from two Harrisburg storms (#6 and #8) were converted to the proper units. Then ultimate load values (Lo) were taken as known in advance. For storm #6 Lo = 610 lbs; for #8, 778 lbs. Notice that in general these values would not be known with certainty. Using STORM ($k = 2$) and SWMM ($k = 4.6$) equations, predicted loadings were calculated for the storms. (To convert from ft^3 to inches, flow was apportioned for STORM by that area of the test basin that was impervious and for SWMM by the total area.) The results are given in Table 5-12. While both STORM and SWMM do a good job of predicting the ultimate loading (Lo), this is not surprising, since the Lo value was assumed given. In fact, for an exponential equation with a "k" value of 2.0 or more the asymptotic load will be attained quite rapidly; as can be seen in the table, past a time of 0.75 hours there is little further washoff.

TABLE 5-12. PREDICTED AND OBSERVED SOLIDS LOADS FOR SWMM/STORM AND FITTED EXPONENTIAL MODELS

time, hrs	cumulative solids observed	SWMM value	STORM value	fitted exponential
Harrisburg Storm #6				
0	0	0	0	0
.33	15.54	9.7	16.0	10.94
.58	271.48	294.4	398.9	276.8
.83	551.15	536.7	589.9	536.7
1.08	591.15	585.7	606.6	601.49
1.33	596.91	601.7	610.0	617.67
2.08	602.81	610.0	610.0	637.83
2.83	607.18	610.0	610.0	654.39
4.08	609.34	610.0	610.0	671.8
7.58	609.96	610.0	610.0	684.58

fitted exponential model:

$$\text{change in solids} = 1233.08(\exp^{(-1.66861\ E\text{-}5)t \times \text{flow}}) \quad R^2 = .981$$

Harrisburg Storm #8				
0	0	0	0	0
.25	6.59	3.85	6.19	9.35
.50	132.3	34.9	55.45	41.49
.75	363.8	278.9	397.29	223.62
1.0	419.8	532.3	656.14	361.50
1.25	574.2	751.4	773.81	542.10
1.5	688.4	777.0	777.0	601.67
1.75	714.8	777.0	777.0	610.27
2.0	772.4	777.0	777.0	624.50

fitted exponential model:

$$\text{change in solids} = 628.918(\exp^{(-5.527\ E\text{-}5)t \times \text{flow}}) \quad R^2 = .389$$

Note: solids in pounds; flow in cubic feet.

In Harrisburg Storm #6, the SWMM formulation does almost as well as the fitted exponential model in predicting cumulative solids, but STORM overpredicts solids. Notice that this was a brief, intense storm which might be expected to produce a classical exponential washoff.

Further, SWMM and STORM first underpredict (in the time period 1/2 hour to .75 hours elapsed time), then overpredict solids for Storm #8. The reason is that this storm exhibits non-uniform changes in slope (see Figure 5-13). Even if we fit the data directly -- obtaining an "individualized" k- value for each storm, (see Table 5-13 and last column of Table 5-12) -- there is much variation, particularly in early periods of the storm, that cannot be accounted for. This is significant because, given this data, it is the best fit any exponential-SWMM-type model could hope to have. If we further generalize the equation and use a fixed k over all storms, as is done in the SWMM or STORM models, then we will do worse.

TABLE 5-13. RESULTS OF EXPONENTIAL MODEL FOR PREDICTING SUSPENDED SOLIDS WASHED OFF OVER AN INTERVAL

Model: $ss_t = x1(e^{x2\ \mathrm{flow}(t-1)} - e^{x2\ \mathrm{flow}(t)})$

where ss_t is suspended solids in pounds, accumulated up to period t

flow(t) is flow accumulated up to and including period t in ft^3

t is time in minutes

Catchment	Event	X1	X2	R^2	Remarks
Harrisburg	1	26.21	8.35 E-4	.773	very few (5) data pts.
	2	206.795	4.994 E-5	.643	double storm
	3	18.045	7.36 E-4	.948	
	5	22.694	1.77 E-4	.138	time intervals are very uneven (scattered showers)
	6	1253.92	1.683 E-5	.981	
	7	99.913	5.49 E-4	.942	
	8	628.92	5.527 E-5	.389	double storm
Milwaukee A	4	6228.1	1.42 E-5	.917	
	5	12939.5	4.46 E-6	.884	
	6	1503.6	6.743 E-6	.894	
	7	13662.5	5.83 E-6	.904	
Milwaukee B	1	99.496	1.33 E-4	.92	

What conclusions for computer modeling can we draw?

- Use of individualized "k" values

First, if data are available, the variation of "k" values from catchment-to-catchment would seem to require individualized fits.

- Different behavior of heavy metals.

  This result is further strengthened by the different behavior of heavy metals from suspended solids. Use of "standard" k values must be considered carefully; metals do not behave as suspended solids do.

- Bad predictions of early storm loads.

  The exponential model by itself cannot do a good job of predicting early variations in solids during some storms. Harrisburg storm #8 shows sections of increasing, then decreasing second derivative suggestive of a second-order differential equation unlike those currently used.

- Alternative functional forms.

  It is possible that some form of a Michaelis-Menton equation or a second-order form as discussed with the loading equation earlier in this section may do a better job of fitting this observed behavior. Because these latter models have two or more parameters rather than the single "k" value in SWMM, they could perhaps be better fit to observed data. This remains to be investigated.

- Importance of good estimation of Lo (maximum potential washoff).

  If one is using SWMM or STORM to predict ultimate loads, then accurate estimation of the Lo term is essential because the models quickly attain that limiting value. As we have seen, accurate prediction of Lo is itself contingent upon careful use of transformed loading values. Given that one cannot use the exponential model for very accurate estimation of early storm loadings, we find it reasonable to place relatively more effort into obtaining good values for Lo so that total storm loads might be predicted. If the Lo value is only guessed at, the use of the exponential equation must be viewed as questionable, for then both of its parameters are possibly in error.

- Need for more early storm measurements.

  Part of the poor results for fits in the early sections of the storms is almost certainly due to the scarcity of observed data from these time periods.

SECTION 6

DEVELOPING PRODUCTION FUNCTIONS FOR RUNOFF CONTROL MEASURES

WHY A SIMULATION MODEL

There is a lack of data on the effects of different on-site runoff control measures. For example, there is only one place known to us where monitoring of water quality runoff of porous pavement has been done: the Woodlands, Houston, Texas (Espey, Huston and Associates, 1976).[1] Since we cannot use test data, one way to obtain some insight into the relative effects of control measures is to simulate a series of experiments utilizing different controls. Given a synthetically modeled site, we do not make accurate predictions of the runoff, but only comparisons among different options. By running the model under a simulated set of randomized trials, we can create synthetic experimental data for each set of on-site options. Just as if we had actually performed such experiments, we can then analyze the effects of different options in a two-way table.

DESIGN OF THE MODEL: HYDROLOGY

Let us look at a schematic representation of the development site (Figure 6-1). We want a procedure to find the hydrograph and pollutographs at a point A, before runoff enters a possible storage/treatment section. An observer at point A sees the effects of site controls only by changes in flows and concentrations at this single point: the development effects are aggregated into a one-measurement location.

A simulation that purports to develop hydrographs must have a space coordinate and a time coordinate to measure the effects of distance and changes in the state of nature, i.e., the time it takes runoff to reach 'A' and the increments of time when rain occurs. In our case, we use the simplest possible coordinates: "blocks of land," i, and "rain intervals," j. Both blocks of land-space- and rain intervals-time- are scaled to be compatible with the selected site: if the time of concentration for the block in question is on the order of a few minutes, the rain interval is also of the same order of magnitude. The details of the model are described in Appendix B; a complete listing of the computer program appears in Appendix C.

THE DEVELOPMENT PATTERNS

The layout of the development site can have important consequences for the hydrologic regime of an area. The model is constructed to easily test

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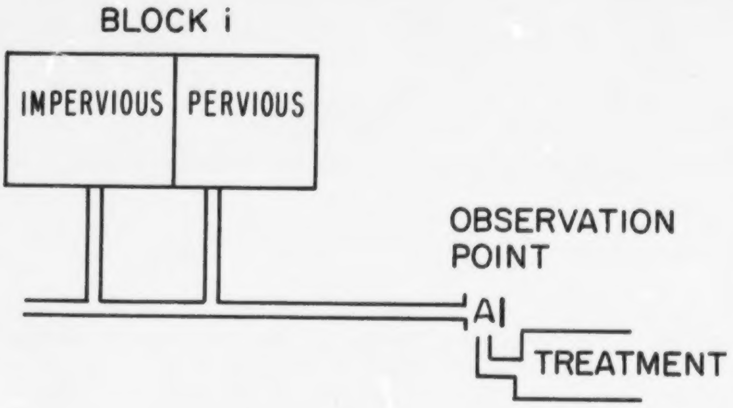
[1] An interesting case study of a porous pavement site appears in Appendix D.

FIGURE 6-1. HYPOTHETICAL DEVELOPMENT BLOCK



alternative development plans: one simply constructs a new set of cells with different areas allocated to the pervious or impervious sub-sections. As the number of housing units increases, for example, the area devoted to "impervious" and "road" grows as well. On the other hand, a "townhouse" type development can put the same number of units onto a smaller land area, with a smaller change in cover. Other model parameters are changed to reflect the different distribution of cell areas.

In this study, three layouts were chosen for simulation:

1. a "conventional" development, with quarter-acre lots;
2. a "low-density" development, one acre lots;
3. a "cluster-townhouse" development, with four units per townhouse, and clusters of three-five townhouses per cell.

These different development patterns were selected so as to incorporate a broad range of alternatives, from those that develop almost all the area of site (alternative 1, conventional) to those that leave most of the area untouched (alternative 2). In addition, alternative 3 (townhouse), allows us to test whether one can put the same number of total units onto an area as in conventional developments, but with less impact on the hydrology.

The following situations were simulated with the three development alternatives.

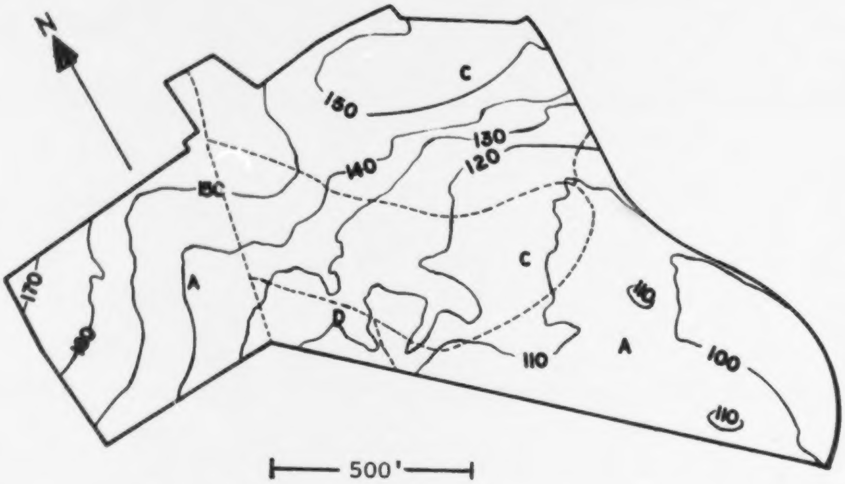
1. Two soil regimes: highly pervious, highly impervious
2. Six control measures:
   a. none
   b. porous pavement
   c. swales
   d. roof-gutter disconnection
   e. on-lot storage
   f. vegetative cover

THE SIMULATION SITE

Bowker Woods, a residential development in Norwell, Massachusetts, was chosen as the simulation site. As one of two areas developed by the subcontractor, BSC Engineering, hydrologic information and detailed maps of soil type and topography were readily available. The total area covered is about 26.4 acres (10.75 ha). Figure 6-2 shows a schematic drawing of the area with U.S. Soil Conservation soil classification as shown: "A" is highly permeable; "B " less permeable; "C " impermeable; "D " highly impermeable (SCS, 1975).

For each of the three site layouts seven or eight simulation model cells were formed. Cells were drawn roughly the same size in each layout. A schematic drawing of each layout is given in Figures 6-3 to 6-5 (see Appendix B for the details).[2]

FIGURE 6-2. BOWKER WOODS DEVELOPMENT SITE



DETAILS OF THE DEVELOPMENT LAYOUTS

Development Number One: Conventional Design

Figure 6-3 shows a conventional layout (quarter-acre lots). A total of 68 units are placed, and simulation cells are as marked on the figure.

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[2] The unnumbered cell in the southeast corner of Figures 6-3 to 6-5 is primarily conservation land and is assumed to be pervious and not draining directly into an impervious area. In the simulation the land in this cell is allocated between the two adjacent cells.

FIGURE 6-3. BOWKER WOODS QUARTER-ACRE DEVELOPMENT ("CONVENTIONAL")

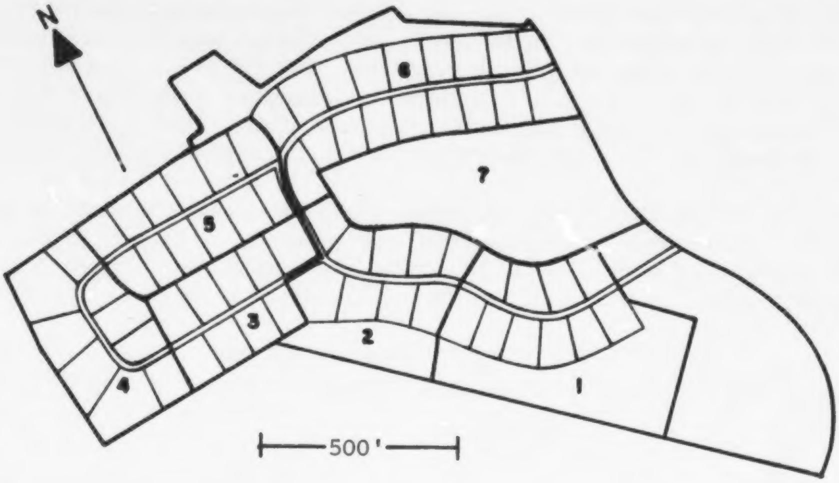

N
6
7
5
3
2
4
1
500'

FIGURE 6-4. BOWKER WOODS LOW-DENSITY DEVELOPMENT

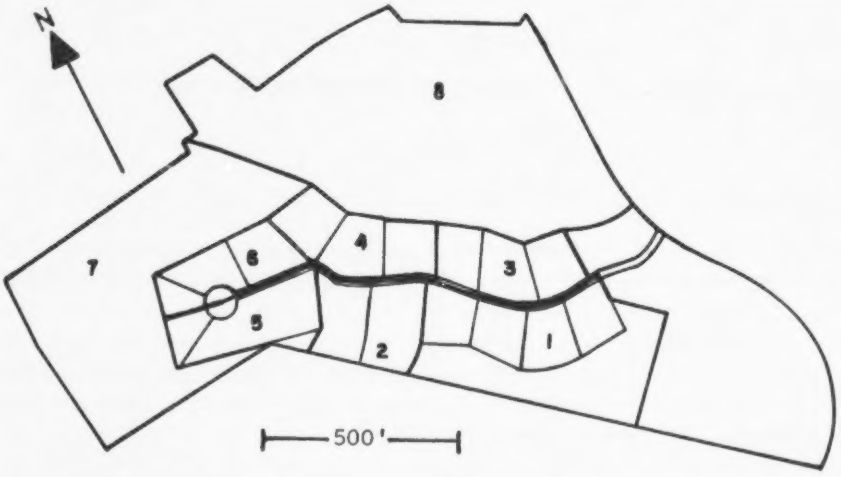
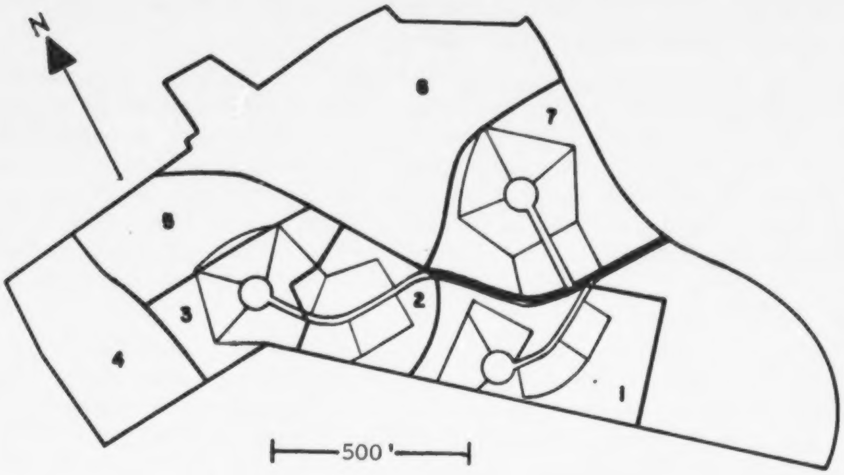

N
8
7
6
4
3
5
2
1
500'

FIGURE 6-5. BOWKER WOODS CLUSTER-TOWNHOUSE DEVELOPMENT



Parameter values for each of the cells and their sub-sections are given in Appendix B, Table B-2. Within each cell the sub-sections are defined as:

1) pervious, draining impervious area (receives runoff from sub-section 4); lawns, open field, etc.;
2) pervious, not draining impervious area;
3) impervious draining to transport system (roof drains, if connected);
4) impervious draining to pervious (driveway, rooftop if not connected to transport system);
5) impervious main road

Development Number Two: Low Density Layout

There are only 16 units placed on the large lots, roughly corresponding to the density proposed in the actual plan by BSC Engineering (ten units). This means that the percent area that is converted to impervious is much smaller for this type of development than for the conventional development (road and house surface area is smaller). Figure 6-4 gives the sketch of the layout. In Appendix B, Table B-3 gives the parameter information for the low-density (one+acre) layout.

Development Number Three: "Cluster" Layout

Each cluster is made up of groups of townhouses, four units/townhouse. There are 17 clusters, for a total of 68 units, so we are constructing the same total number of units as the conventional layout. Further modifications include the cul-de-sac roads that lead into each cluster; this adds to the surface area taken up by roads. Table B-4 (Appendix B) presents information for the "cluster" development. A sketch of the layout is given in Figure 6-5.

ANALYSIS OF RESULTS OF THE SIMULATION MODEL: CONSTRUCTING PRODUCTION FUNCTIONS FOR ON-SITE CONTROL MEASURES

The effects of on-site controls. Table 6-1 presents a summary of the mean peak flow from ten randomized trials drawn from storms of a given volume and rainfall distribution. The rows represent the three developments and the columns list the control measures. The value within a particular cell in a row and column is the mean peak flow over the storms for that development (row) and control measure (column); in this way the table gives a comparison among all possible combinations of development types and control measures. Tables 6-2 to 6-4 give corresponding results for total flow, peak solids and total solids.

Returning to Table 6-1 we can analyze this table as if it were a real experiment with a set of treatments (control measures) and a set of experimental "plots" (development types). In order to separate the effects of different developments and controls, either classical analysis of variance or two-way table methods could be used. Further, we then can see whether the effects of certain control combinations are additive -- that is, is the change in flow from porous pavement control to porous pavement and vegetative cover control the same as adding the changes from porous pavement and vegetative cover separately?

Figures 6-6 and 6-7 provide a better way to compare the options; they give ratio changes of effects, comparing the conventional/no control cases. Without any additional analysis it is easy to see that the low density development has greatly reduced flow and solids (baseline = conventional development). This is not surprising, since a smaller portion of the site is impervious in this development. Further, one notes that porous pavement has a stronger effect in reducing flow and solids than any other single control measure. Nonetheless, it is crucial to use a two-way analysis to analyze the results because it separates the total change in flow into a model where the effects are additive.

flow = development types effect + control measure effect + common value + residual

We cannot merely assume, however, that the effects of different options and developments are additive. In fact, they are not: there is almost a perfect factorial interaction between development type and control option. That is, the effect of having porpous pavement and low-density housing is multiplicative. This multiplicative interaction can also be fit into the two-way tables. The model then becomes:

flow = development type effect + control measure effect
+ interaction (development x control)
+ common value
+ residual

The results of the two-way analysis appear in Table 6-5. The remaining residuals, as displayed below the two-way table, show no clear pattern, so that we may assume that the model is additive as given. However, there are

TABLE 6-1. PEAK FLOW (CFS) SIMULATION MODEL

1" Storm Volume
Mean of 10 Simulations per cell

control measure

development type	N	PP	V	R	ST	SW	I	PP V	PP V I	PP V R	PP V SW	PP SW	PP ST	PP R	PP R SW	PP R SW ST	PP R SW ST V
low density	.022	.015	.023	.024	.022	.020	.021	.016	.014	.016	.016	.016	.015	.015	.020	.015	.015
cluster	.135	.090	.136	.133	.131	.123	.129	.088	.088	.081	.092	.068	.061	.063	.070	.063	.068
conventional	.181	.101	.179	.174	.173	.163	.167	.099	.092	.100	.104	.100	.082	.081	.084	.081	.083

Key: N = no controls
PP = porous pavement
V = vegetative cover
R = roof-drain disconnection
ST = on-lot storage
SW = swales
I = impervious soils

TABLE 6-2. TOTAL FLOW FROM SIMULATION MODEL (inches)

1" Storm Volume
Mean of 10 Simulations per Cell

control measure

development type	N	PP	V	R	ST	SW	I	PP V	PP V I	PP V R	PP V SW	PP SW	PP ST	PP R	PP R SW	PP R SW ST	PP R SW ST V
low-density	.091	.058	.091	.091	.091	.091	.113	.058	.058	.058	.058	.058	.058	.058	.058	.058	.058
cluster	.722	.462	.719	.729	.726	.730	.791	.463	.541	.462	.465	.270	.272	.276	.269	.278	.240
conventional	.760	.430	.723	.807	.774	.791	.956	.411	.546	.393	.432	.456	.462	.463	.457	.465	.464

Key: N = no controls
PP = porous pavement
V = vegetative cover
R = roof-drain disconnection
ST = on-lot storage
SW = swales
I = impervious soils

TABLE 6-3. PEAK SOLIDS FROM SIMULATION MODEL (lbs)

1" Storm Volume
Mean of 10 Simulations

control measure

development type	N	PP	V	R	ST	SW	I	PP V	PP V I	PP V R	PP V SW	PP SW	PP ST	PP R	PP R SW	PP R SW ST	PP R SW ST V
low-density	7	1.7	2.3	2.1	2.0	1.8	1.9	1.5	1.5	1.8	1.9	1.8	1.8	1.8	2.1	1.7	1.6
cluster	19.2	9.3	13.8	10.7	11.2	10.6	11.2	9.1	9.4	9.2	10.2	9.6	8.7	7.9	8.1	7.6	8.1
conventional	25.9	10.8	17.5	14.2	14.2	13.6	13.9	10.3	10.8	12.0	12.3	17.6	11.4	10.	9.9	9.5	9.9

Key: N = no controls
PP = porous pavement
V = vegetative cover
R = roof-drain disconnection
ST = on-lot storage
SW = swales
I = impervious soils

TABLE 6-4. TOTAL SOLIDS FROM SIMULATION MODEL (lbs)

1" Storm Volume
Mean of 10 Simulations per Cell

control measure

development type	N	PP	V	R	ST	SW	I	PP V	PP V I	PP V R	PP V SW	PP SW	PP ST	PP R	PP R SW	PP R SW ST	PP R SW ST V
low-density	17	6	8	7	7	7	10	5	7	6	6	9	7	6	6	6	6
cluster	63	45	60	57	57	57	66	45	53	49	50	51	36	32	32	32	26
conventional	72	45	59	64	61	60	76	42	56	46	51	71	62	53	54	51	52

Key: N = no controls
PP = porous pavement
V = vegetative cover
R = roof-drain disconnection
ST = on-lot storage
SW = swales
I = impervious soils

FIGURE 6-6. EFFECTS OF CONTROL MEASURES AND DEVELOPMENT TYPES ON RUNOFF

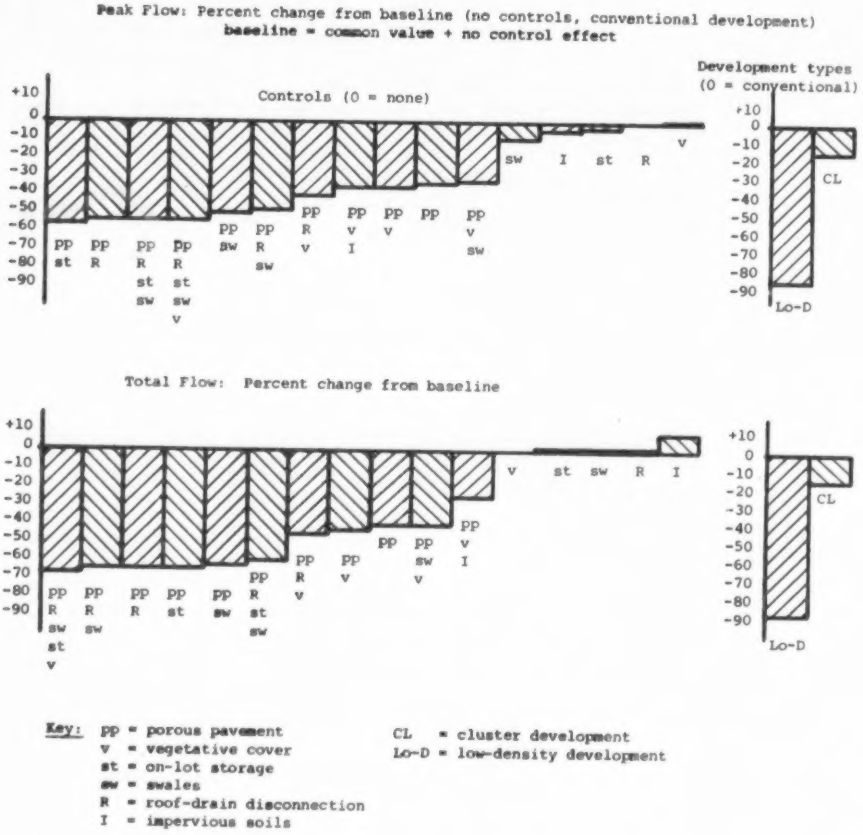


FIGURE 6-7. EFFECTS OF CONTROL MEASURES AND DEVELOPMENT TYPES ON SOLIDS RUNOFF

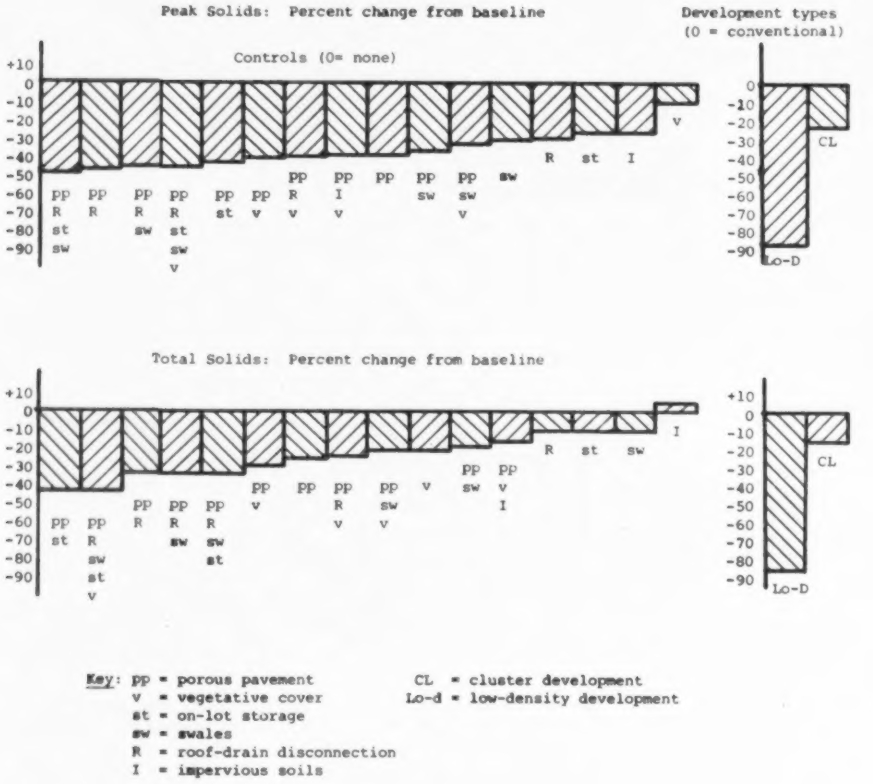


TABLE 6-5. TWO-WAY ANALYSES OF PEAK FLOW EFFECTS

control measure

development type	N	PP	V	R	ST	SW	I	PP V	PP V I	PP V R	PP V SW	PP SW	PP ST	PP R	PP R SW	PP R SW ST	PP R SW ST V	Development type effect
low density	0	.001	0	.003	.001	0	0	.002	0	.003	.001	.005	.005	.005	.009	.005	.004	-.074
cluster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
conventional	.016	-.008	.013	.012	.013	.013	.010	-.008	-.015	.001	-.008	.017	.008	.004	-.001	.004	0	.019
control measure effect:	.047	.002	.048	.045	.043	.035	.041	0	0	-.007	.004	-.02	-.027	-.025	-.018	-.025	-.02	.088 (common value)

```
residuals                                    peak flow = common value + control measure effect
 x  .001                                                              + Development type effect
     |  0                                                             + control x development effect
  16 |  0                                                             + residual
  14 |
     |  0
  12 |  0
     |  0
   8 |  00
     |  0000
   4 |  000
     |  000
     |  000
  +0 |  00000000000000000000000
  -0 |  50
     |
  -4 |
     |
  -8 |  00
 -12 |
     |  0
 -16 |
     |  median = 0.0
```

large remaining residuals for some cells in the "conventional" development type that remain unaccounted for. Roughly, the residuals are too positive for small positive effects and too negative for negative effects. Because of this, it is important to note that small differences in effects from one control to another are not important because the "error" is larger than such differences.

Briefly, the two-way analysis demonstrates that the low-density development reduces peak and total flow more than any other single factor. (The reduction is about 87 percent.) A cluster-townhouse development lowers flow and solids by about 15 to 20 percent. Though no on-site control measure is as effective as low-density development, porous pavement is the clearly dominant single control. As Figure 6-6 illustrates, porous pavement alone reduces peak flow by 33 percent and total flow by 40 percent. Combined with the additional measures of swales, storage, or roof drain disconnection, additional reductions of about 10-20 percent are attainable, but -- and this is significant -- there is a diminishing rate of return. With three controls, or even four or five, an additional reduction of only a few percent is achieved.

Because the two-way model is additive, we can use the effects ratio to construct "production function" curves using marginal percent effectiveness to incrementally select those control measures that have the largest impact in flow and solids reduction (see Figure 6-6). (The ranking of controls is generally consistent across all of the summary measures of storm events used: peak and total flow and peak and total solids, as well as across all development types.)

Incremental Control Measure	Incremental Reduction in Peak Flow
porous pavement	33
+ storage	22
+ swales	-2
+ roof-drain disconnection	0
+ vegetative cover	0

	Incremental Reduction in Total Flow
porous pavement	40
+ storage	23
+ swales	0
+ roof-drain disconnection	0
+ vegetative cover	4

	Incremental Reduction in Peak Solids
porous pavement	39
+ roof-drain disconnection	9
+ swales	-1
+ storage	3
+ vegetative cover	-3

	Incremental Reduction in Total Solids
porous pavement	25
+ storage	18
+ swales	-10
+ roof-drain disconnection	0
+ vegetative cover	10

It is important to notice that the effects of control measures are not generally additive: use of porous pavement reduces peak flow by 33 percent (effect .002), and swales reduce peak flow by ten percent (effect .035), but the effect of porous pavement and swales is a reduction of 53 percent -- not an additive change. Also, as demonstrated, control measure and development type effects are multiplicative. Under different storm volume conditions around one inch (from .7 to 1.3 inches), the results are about the same.

For extremely low storm volumes of about .1 inch, so little runoff is produced that control effects are hard to distinguish, but they are not necessary in any case. For extremely high volumes of very short duration (1.80 inches in ten minutes!), all control measures seem to fail equally (this is also to be expected). These low and high volume conditions seem to bound the middle storms that represent conditions for which on-site control measures would be designed. The marginal ranking of effectiveness therefore seems to hold for a large range of conditions that are of interest.

CONCLUSIONS

On-Site Controls

- The simulated-reduction of flow/solids via on-site control measures shows a maximum reduction effect of 50 percent.
- Much of this reduction can be achieved through the use of just one control, porous pavement. This is an important finding, especially coupled with the case-experience with porous pavement discussed in Appendix D.
- Additional controls such as swales, on-lot storage, or roof-drain disconnection, have a much smaller effect alone than porous pavement. Used with porous pavement, there is a diminishing rate of effectiveness.

Development Types

- The density of development is the largest single factor in reducing runoff.
- The interaction between control measures and development types is multiplicative. Therefore, one gains multiplied benefits from porous pavement and a low-density development. This has important consequences for planning runoff control in new developments.
- Cluster development modestly controls runoff.

Use of Simulation Techniques

- Two-way analyses of development and control types can be made via a simulation model to yield "production function" rankings of control measures. Of course, the ultimate validity of the rankings can only be verified by field measurement. (For example, data on porous pavement runoff is lacking.) However, this section does demonstrate the feasibility of the simulation method in the study of control measure comparisons.

SECTION 7

STOCHASTIC MODELS

INTRODUCTION

The underlying theme in the preceding discussion of accumulation of pollutants, washoff, and the effects of control measures is the stochastic nature of these processes. This is nowhere more apparent than in the storm events that drive the washoff itself. Any single observed storm is but one from a potentially infinite variety of storms. How then can any single, idiosyncratic storm event successfully represent the full range of conditions that will actually be encountered? Engineers have countered with the use of artificially constructed "design storms," but McPherson (1977) has cogently argued that the idea of such a synthetic storm is inherently faulty, in that its artificial creation gives it properties that would never be observed in nature.

What a decision maker must face is not the occurrence of any particular "design storm," but rather a set of chances of pollution events of varying sizes. The game is a gamble against these outcomes through bets made in the form of control strategies. It is in this larger sense that the use of a design storm is perhaps weak: it ultimately conceals from the decision maker information on the distribution of states of nature.

Another way to incorporate these stochastic effects is to place them directly into the models that are proposed. For example, this was done in the simulation of control options in Section 6 by randomly sampling storms from a given distribution as if they had actually been observed. In this section we present three models that also confront the issue of stochasticity head on by using probability distributions of storm volumes and pollutant surface loadings to find the probabilities of overflow and washoff (Flatt and Howard, 1978).

The first model demonstrates that the use of "design storms" does in fact represent an implicit cost-minimization decision problem in sewer design based on storm frequencies. In contrast, the design storm approach does not address the cost in tradeoffs in storm frequency versus sewer design explicity. This may be considered good or bad.

A second, related model proceeds to attack the inverse problem; given a designed system, what is the chance of overflow events? Here the question is not so much one of cost-minimization of sewer construction (which is already in place), but rather a consideration of prediction of adverse effects.

Finally, the third model is one to be used in the planning of a new residential development where neither of the other models, which assume conventional sewers, apply. Using the roughest assumptions about the distribution of runoff volumes and initial load, the distribution of washoff solids from an area is estimated.

All three of the models suffer from mathematical difficulties inherent in the nature of probabilistic calculations: unless the functional forms are quite simple (normal, exponential, log-normal), the resulting computations are usually intractable. Nonetheless, even with these simplistic assumptions we can demonstrate the use of probabilistic models in decision-making; they can provide general guidelines for planning before detailed computer models are required (Hydroscience, 1976).

MODEL #1: STORM DRAINAGE DESIGN

Storm drainage systems conduct unwanted runoff to the nearest acceptable discharge point. While it might be desirable to provide channels adequate for the greatest storm for which there are local records, such a design would usually require prohibitively large expenditures. Consequently, systems of modest capacity have been installed in urban areas of the nation. How have the capacities of these systems been determined? In discussing storm sewers, Engineering Manual #37, Design and Construction of Sanitary and Storm Sewers (1970), states that

> ...An economic balance is necessary between the cost of structures and the direct and indirect costs of possible damage to Property and inconvenience to the public over a long period of years . . . The average frequency of rainfall occurrence used for design determines the degree of protection afforded by a given storm sewer system...

However, without a definition of damage and a procedure for estimating it, these statements are non-operational. In acknowledging the difficulty the Manual continues

> But in practice, cost-benefit studies usually are not conducted for the ordinary urban storm drainage project. Judgement supported by records of performance in other similar areas is usually the basis of selecting the design frequency.

In engineering offices the range of design frequencies used is usually two to fifteen years for residential areas (with five years most commonly reported) and ten to fifty years for commercial and high-value districts.

Such guidelines are not new. Advice similar to that above can be found in standard engineering textbooks. For example, writing more than 50 years ago, Metcalf and Eddy (1914) stated that

> Few problems have afforded the sewer deigner more misgivings than the determination of the quantity of stormwater for which storm drains or combined sewers should provide. The chief reason for this

> lies in the fact that the problem is indeterminate, and that the information which may be available and the formulas which may be used only serve to aid his judgement, upon the soundness of which the correctness of final solution very largely depends. In fact, it is a difficult task to say when the solution of such a problem is correct within the usual meaning of the term...

On the topic of benefit-cost analysis, they concluded

> Practically, however, such computations are of little significance. Local circumstances and conditions, physical and financial, have usually a controlling effect upon the extent to which such drains can be designed to care for extreme maximum rainfalls.

Unlike the Manual, Metcalf and Eddy explictly included financial capability as an important controlling factor in selecting the degree of protection. They also pointed out that legal responsibility of the community is a consideration since any damage from flooding must be borne by members of the community. The courts have held that

> ...rainfalls are differentiated for judicial purposes into ordinary, extraordinary and unprecedented classes. Ordinary rain storms are those which may be reasonably anticipated once in a while, and unprecedented storms are those exceeding any of which a reliable record is extant. The usual rule in determining the responsibility of a city was stated many years ago by the New York Court of Appeals, 32 N.Y. 489 as follows: 'If the city provides drains and gutters of sufficient size to carry off in safety the ordinary rainfall, or the ordinary flow of surface water, occasioned by the storms which are liable to occur in this climate and country, it is all the law should require'. (Eng. Rec. June 18, 1912).

What constitutes an "ordinary" storm? Is a storm which is expected to occur on an average once in ten years ordinary? In some localities the testimony of an engineer is sufficient evidence of what is an extraordinary rainfall. However, no two engineers acting independently would always reach the same conclusions as to storm events. Therefore the question of ordinary and extraordinary still remains.

The second half of the 19th century witnessed intensive efforts in rainfall data collection and analysis in this country. The relationship between the intensity of a rain and its duration was studied for the needs of storm drain design. Some of the original work was done by Talbot (1899), who, making use of U.S. Weather Bureau records at 499 stations plotted storm intensities against durations on a cross-section paper. Two envelope curves were drawn, one giving what might be called the very rare rainfalls, and the other the ordinary maximums. The curves were in both cases rectangular hyperbolas. Their equations were determined to be

$$i = \frac{360}{t+30} \qquad (7\text{-}1)$$

for the curves of rare occurrence, and

$$i = \frac{105}{t+15} \tag{7-2}$$

for those of frequent occurrence, where i is the rainfall intensity in inches per hour, and t is the duration of the storm in minutes.

Since Talbot constructed these curves, many cities, public agencies, and engineering firms have developed similar equations as a basis of storm drain design. For example, Boston has used $i = 150/(t+30)$, a relationship very much like equation (7-2). Such expressions serve as a first step in developing designs of storm drainage systems, but the degree of protection is still based on judgement, financial capability and legal responsibility.

A Decision Model

To put questions of protection into perspective, we have formulated a model of the design problem. For a given urban area with known specified topography, geology, and land use patterns, let the storm sewer cost be denoted as K(i), damage caused by inundation of property as D(i), where i represents the rainfall intensity. Let the density function of rainfall intensity be f(i). One decision problem is to select a sewer system with capacity adequate to accommodate runoff caused by rainfall intensity less than or equal to i and minimize the total cost (τ is dummy variable of integration)

$$Z = K(i) + \int_i^{\infty} f(\tau)\, D(\tau)\, d\tau \tag{7-3}$$

Rousculp (1939) has shown that there are substantial economics of scale in storm sewer construction. We therefore approximate the cost function by $K(i) = \alpha i^{\beta}$. Property damage depends on the depth of inundation, which is influenced by the rainfall intensity and storm duration. For demonstration purposes only, we may assume that the damage is a constant value for all i. With these simplifications equation (7-3) becomes

$$Z = \alpha i^{\beta} + D\{\, 1-F(i) \,\} \tag{7-4}$$

Optimum condition, $dZ/di = 0$, implies that

$$Df(i) - \alpha\beta i^{\beta-1} = 0 \tag{7-5}$$

If we assume $f(i) = 1.2e^{-1.2i}$ and if we specify, based primarily on Rousculp (1939), that $\alpha = 2770$, $\beta = 0.27$, $D = 7400$, we can solve the equation to obtain

$$i^* = 2.66 \text{ inches/hour}$$

$$K(i^*) = 2770 \times 2.66^{0.27} = \$3607/\text{acre}$$

$$1-F(i^*) = e^{-1.2 \times 2.66} = .041$$

$$T^* = 1/(1-F(i^*)) = 24.3 \text{ years}$$

Where T^* is the design storm frequency.

As discussed above, the financial capability of a community plays an important role in sizing the sewer system. To include this consideration, appropriate constraints can be incorporated in the model.

Data Problems

In equation (7-5) (optimum condition), the computation of i^* requires the estimation of parameters D,[1] α, and β. Any errors associated with these estimates can cause changes in the optimum solution, and in turn alter the design and construction costs. To explain the argument, we differentiate equation (7-5) to obtain

$$\Delta i = \{ (\alpha\Delta\beta + \beta\Delta\alpha) i^{\beta-1} - f(i)\Delta D\} / \{ Df'(i) - \alpha\beta(\beta-1) i^{\beta-2}\} \qquad (7\text{-}6)$$

This equation shows that changes (Δi) in i^* are a function of parameters' values, their changes, and functional forms used to describe rainfall intensity and sewer costs. The changes in i cascade down to design via the rational formula $Q = CiA$. Changes in i also affect the selection of C.

$$\text{Hence } \Delta Q = (AC + Ai \frac{\partial C}{\partial i})\Delta i. \qquad (7\text{-}7)$$

To test the effects of errors in parameters and the misspecification of functional (or model) form on the solution, sensitivity analysis is frequently performed.

Rainfall data are often only a short string of observations out of a large population; the observed events are unlikely to repeat themselves in the basin. However, population parameter estimates based on observed data may be non-representative of events arriving during the life of the project. Kirby (1974) has shown that moment estimates are constrained by the number of observations in the data. Slack, et al.,(1975), have demonstrated, by Monte-Carlo experiment, that there is a substantial difference between the estimated skewness of the observed data and that of the population. They have also shown that transformations to facilitate analysis, particularly the log transform, are dangerous because small errors of estimation in log space are vastly amplified when transforming back to the raw data space. It appears from all these studies that robust distributions to model hydrologic phenomena should be used rather than complicated distributions which require the estimation of higher moments.

There is another difficulty in using rainfall data for storm sewer design: records are available only for a limited number of locations. It is unlikely that a specific project area will possess a rain gage. Transferring information to the project site from other areas introduces errors in estimation. Moreover, rainfall data are often measured in hourly intervals, and only in limited areas are more refined data collected. To be useful for storm sewer design, hourly data must be decomposed on the basis of shorter time intervals. This task can also cause error in design event estimation.

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[1] In an actual application D is a function of depth of inundation.

MODEL #2: HYDRAULIC CAPACITY OF A TREATMENT SYSTEM

The dry-weather wastewater flow of a city, since it is composed of domestic wastewater, commercial/industrial waste, and infiltration, varies in quantity depending on the season, day of the week, and the hour of a day. In large cities peak dry-weather flow varies from two to four times the daily average, while in small communities the ratio may be higher. Interceptor sewers and treatment systems are customarily designed with a capacity of peak dry-weather flow, whereas in a combined sewer system the facilities are used to accommodate some storm runoff. To some extent the ability of a given system to convey and treat stormwater depends on the quantity of dry flow being discharged at the time the storm occurs. During peak dry flow any surface runoff reaching these facilities will cause overflows to occur. On the other hand, these facilities will have capacity for more stormwater if rainfall occurs when the flow of dry flow is small. Inasmuch as rainfall shows little tendency to favor certain hours of the day, the probability of surface runoff coinciding with peak dry-weather flow is balanced by the probability of rainfall during periods of low dry flow. Hence the average capacity of the system for storm runoff can be estimated on the basis of the mean dry-weather flow and the system's design capacity. If the interceptor and treatment system are sized to take an average of twice the dry-weather flow, then in the long run a quantity of storm runoff equal to the dry-weather flow will be treated during the periods of rainfall. If the system's capacity is three (or n) times average dry flow, the storm runoff treated will increase to two (or n-1) times average dry flow. To control all or almost all stormwater requires a large system -- too expensive to be borne by most communities. In reality overflows are permitted and raw sewage is discharged along with the storm water.

On the basis of the long run average posited above, McKee (1947) analyzed the Boston sewer system to determine the percentage of time that overflows occur, the proportion of sanitary sewage escaping, and the number of separate and distinct storms that cause overflows. With a capacity of twice the dry-weather flow, on the average 2.68 percent of total sewage would be lost through overflows occurring five to six times a month between June and November. From his analysis a capacity larger than three times dry flow would not be economically justified. By following the same procedure Stanley (1947) studied the sewer systems of Chicago and Minneapolis and reached a similar conclusion.

In essence the method employed by both McKee and Stanley is the estimation of the probability distribution of the sum of dry-weather flow plus storm runoff -- Pr $(D+Q)$, where D stands for dry flow, and Q for storm runoff. Overflow occurs when the sum of flows exceeds the capacity, aD.[1] The probability of the event is $\Pr\{(D+Q) > aD\}$. By field measurements on an existing system, the probability of (D+Q) can be estimated. However, for the long-run case, described above, the problem can be simplified to one of estimating $\Pr\{Q > (a-1)D\}$. Using the rational formula, the overflow probability becomes $\Pr\{i > (a-1)D/AC\}$, in which A is the sewered area that has a runoff coefficient C.

In a storm initial precipitation wets the ground surface and fills depressions. Runoff occurs only after the total precipitation exceeds the initial requirement. Hence rainfall records that are to be used in estimating runoff must be corrected accordingly.[2] For each storm excessive rainfalls (observed rainfall minus depression storage), intensity, duration, volume, and antecedent dry period are estimated. These attributes for all storm events in a given period (e.g., five years or more) are summarized statistically and fitted by an appropriate function. For example, a gamma distribution of the form

$$f(i) = \lambda/\Gamma(r)\ (\lambda/i)^{r-1} e^{-\lambda i} \qquad (7\text{-}8)$$

is often used to describe intensity frequency. Here the parameters r/λ and r/λ^2 represent the mean and variance of intensity and can be estimated by the method of moments. Using this formulation, the probability of overflows then becomes

$$\Pr\{i > (a-1)D/AC\} = {}_0\int^{(a-1)D/AC} f(i)\,di \qquad (7\text{-}9)$$

To illustrate the evaluation of overflow probability, let $r/\lambda = 0.025''$/hour, $r/\lambda^2 = 0.0068''$, a = 3, D = 4500 gallons/day (= 0.007"/hr./acre), C = 0.7, unit area A = 1 acre, then

$$(a-1)D/AC = 2 \times 4500 \times 12/(7.5 \times 43{,}560 \times 24 \times .7) = 0.020''/\text{hour}$$

and

$$\Pr(i > 0.02) = 1 - {}_0\int^{0.02} \frac{3.67}{\Gamma(0.092)} (3.673i)^{-0.0908} e^{-3.673i}\,di \approx 0.35 \qquad (7\text{-}10)$$

This calculation implies that on the average the overflow takes place for about one-third of the storm events. For a = 4, the system can reduce the overflow probability to about 21 percent in this example.

Since the rate of overflow is CiA - (a-1)D, the expected value of this quantity can be estimated as $\int f(i)\{CiA - (a-1)D\}di$. For the case of a = 3, the expression becomes ${}_{0.02}\int^{\infty} f(i)(0.7i - 0.014)di$. If complete mixing between sewage and storm water is assumed, the sewage that overflows (as a fraction of the total overflow) is $\{CiA - (a-1)D\} \div (CiA+D)$. For the case of a = 3, expected percent of sewage overflow during storm events is

---

[1] The coefficient a is the multiplier on dry weather flow and signifies design capacity.

[2] For the Boston area, an allowance of 0.03" is appropriate for the depth of composite storage during summer and fall months.

$$\int_{0.02}^{\infty} f(i)\ \frac{0.7i - 0.014}{0.7i + 0.007}\ di \qquad (7\text{-}11)$$

To estimate analytically the amount of a pollutant in the overflow mixture, two quantities must be known: (i) the deposit or accumulation rate of sewage in the sewer system; and (ii) the accumulation rate of dirt and other contaminants on the land.

MODEL #3: STOCHASTIC WASHOFF

We would like to formulate a model that gives an estimate, in the simplest way possible, of the average kind of washoff event we would expect to see, given a local storm distribution. Such a model could provide the planner with the probability of washoff event as well as the typical variation to be expected. The following is a proposed demonstration of the method to be used to derive such a model. It cannot be used for "real" planning because, as shown in Section 5, the functional forms used probably do not adequately describe the washoff process. However, it can be viewed as a demonstration of the usefulness of the stochastic point of view.

Washoff is assumed to follow the equation

$$L = Lo(1-\exp(-krt)) \qquad (7\text{-}12)$$

Where L = washoff, lbs/unit area

r = runoff, inches/hour

t = time, hours

Lo = initial loading on surface, lbs/unit area

k = constant, about 1-1.2 after unit conversion,

(from Sartor and Boyd, 1972)

We want to find the probability distribution of load under first flush conditions ($t = 0$ to about 0.5 hours). First, we transform to a log scale:

$$\ell nL = \ell nLo + \ell n(1-\exp(-krt)) \qquad (7\text{-}13)$$

Now, given that we want to find the distribution of L in the early stages of the storm, what are the values of 1-exp (-krt)? Here k is about 1.2, r is less than 0.5 (in/hr) and t is less than 0.5. The product krt ranges from 0 to 0.3. In this interval 1-exp(-X) is approximately equal to X (For X = .05, 1 - exp(-X) = .049 for X = .15, 1 - exp (-X) = .139.)[3] For this first flush interval we therefore replace the function 1 - exp(-krt) by krt. We are left with

$$\ell n(L) = \ell n(Lo) + \ell n(krt) \qquad (7\text{-}14)$$

$$= \ell n(Lo) + \ell n(kV) \qquad (7\text{-}15)$$

where V = runoff volume.

The probability distribution of the load during first flush is then the convolution of two probability distributions $\ell n(Lo)$ and $\ell n(kV)$. Now Lo, the initial surface loading, is log-normally distributed (see Section 5). Hence $\ell n(Lo)$ is normal (Figure 5-3). How is $\ell n(kV)$ (the log of runoff volume in the initial half-hour of a storm) distributed? This is uncertain, but if we plot the runoff volumes from Colston (1974) in a stem-and-leaf display, there is a rough log-normal shape (Figure 7-1).[4] Given all these assumptions, the probability of the washoff is then simply the sum of two normal distributions that have been log-transformed. The mean washoff is then (in log scale) the sum of the means of $\ell n(Lo)$ and $\ell n(KV)$:

$$\text{average } \ell n(L) = \text{average } \ell n(Lo) \text{ and average } \ell n(kV) \qquad (7\text{-}16)$$

AN EXAMPLE

Using estimates for k, mean Lo, and V, we can now find expected washoff. One difficulty is obtaining values for runoff volume, V. The sources used here is Colston (1974), samples from a 1069-acre basin in North Carolina (433 ha), of which 833 acreas (377 ha) are residential, industrial, or commercial, and 30 percent is impervious. For this basin two distinct log-normally distributed sets of first-flush (less than 15 minutes) volumes are apparent. The first, smaller volume group has a mean first-flush flow of 4.65 cfs (.16m^3/sec) (see Figure 7-1). For these 14 storms the mean suspended solids concentration is 1024 mg/ℓ (see Figure 7-2). Assuming the Colston study's value of 18 lbs/acre suspended solids loadings for developed areas,

$$\ell n(L) = \ell n(18 \text{ lbs/acre x } 833 \text{ acres}) + \ell n \left[1.2 \text{ x } \frac{4.65\text{cfs}}{320.7 \text{ acres impervious}}\right]$$

$$\ell n(L) = 5.56$$

$$L = 260.89 \text{ lbs}$$

---

[3] This is derived from the Taylor series expansion of $1-e^{-x} = x - \frac{x^2}{2!} + \frac{x^3}{3!} - \frac{x^4}{4!} \cdots$

[4] Other common distributions (exponential, for example) could also be used here. The choice of a log-normal is suggested by the mathematical convenience and a brief look at the Colston data.

Which is converted to mg/ℓ: $\text{mg}/\ell = 267 \ \frac{\text{lbs/min}}{\text{cfs}}$

for 15 minutes = $\frac{260.89}{15 \times 4.65} \times 267 = 999 \ \text{mg}/\ell$

Taking the second, larger-flow group of storms, mean flow is 85.25 cfs (see Figure 7-1). Here, to get a good estimate of the washoff, it is necessary to use a larger value of k (=2.0), than in the preceding set of storms. This gives a predicted mean suspended solids value of 1879 mg/ℓ for initial periods of the storm, compared with an observed average concentration of 2268 mg/ℓ. It can be seen that the predicted average concentration is sensitive to the value of "k" selected, but there is no real experimental data on which to base any justification for the value used. We have only the data of Sartor and Boyd (1972) for street surface runoff (values in converted units for the calculation above range from 1.2 to 2.0). Data for other particle sizes and land surfaces are nonexistent.

Considering the unreliability of the loading, volume, and "k" values, it must be considered fortuitous that the model is accurate in the two cases tested; however, it does in any case give correct order-of-magnitude estimates which could be used at a general planning level. What are the implications for stormwater planning? First, the estimated average first-flush loading of suspended solids in log scale is made up of two components -- initial load and runoff volume. Perhaps more importantly, the variance -- how uncertain we are of what the true expected load is -- is also the sum of the variances for initial load (Lo) and runoff volumes (V). To reduce the uncertainty, one can reduce either the variance of Lo, or that of V. We have seen in Section 5 of this report that even after accounting for solids loading by land use or climate there is often a large remaining variation in load due to wind, traffic, or other microclimatic effects. But these may be beyond control for, as the San Jose study shows, even with street cleaning in a single location, loading is subject to large variations. In contrast, the variance of runoff volume is possible under direct control of planners through the management techniques discussed in Section 6.

FIGURE 7-1. FIRST-FLUSH VOLUMES FROM COLSTON, 1974 (FT^3/SEC)

```
11 |2                          11 |2
10 |0                          10 |
 9 |                            9 |
 8 |                            8 |
 7 |                            7 |
 6 |3       n=14                6 |3       n=8
 4 |                            4 |
 3 |292                         3 |29
 2 |30886                       2 |849
 1 |0                           1 |8
 0 |9                           0 |
low volumes                   high volumes
unit = 1 cfs                  unit = 10 cfs
mean = 4.65                   mean = 88.5
```

FIGURE 7-2. SUSPENDED SOLIDS FROM COLSTON, 1974 (MG/ℓ)

```
  3400
  2710

11 |0
10 |
 9 |2
 8 |
 7 |                           7 |
 6 |6       n=14               6 |7       n=8
 5 |3                          5 |
 4 |                           4 |4
 3 |40                         3 |5
 2 |43                         2 |6
 1 |17                         1 |1
 0 |57                         0 |184
low volumes                  high volumes
unit = 100 mg/ℓ              unit = 100 mg/ℓ
mean = 1024 mg/ℓ             mean = 2268
```

SECTION 8

ESTIMATING COSTS OF ON-SITE CONTROL MEASURES

As pointed out earlier in this report, the lack of appropriate cost relationships makes it difficult to prepare meaningful cost-effectiveness analysis of stormwater control options. In this section we explore methodologies for obtaining generalized cost functions. Ideally, we would like to develop functional relationships between costs and certain factors which are available at the preliminary planning level. These factors typically include general site characteristics, such as slope, size, and intensity of development and meteorological information such as the design storm. At this level of analysis engineering design data (such as the size and length of drainage pipes and the maximum discharge) would not be available. Thus cost estimates at this level will of necessity be crude relative to estimates made later in the design process. If properly developed, however, they would be useful in evaluating area-wide stormwater management strategies and comparing alternative combinations of measures.

Our analysis has focused initially upon the evaluation of traditional drainage system costs. This choice is based upon two considerations:

1) In most areas conventional storm sewer systems represent the current practice against which options such as on-site storage will inevitably be compared. Thus it makes sense to treat the conventional system as a baseline for cost evaluation purposes.

2) Since conventional storm sewer systems are widely applied, there is more knowledge and data on costs for this system than for other measures. Cost estimating approaches can be tested against a conventional system before extending them to measures for which cost data are limited or unavailable.

PREVIOUS STUDIES

In order to establish cost functions of the type desired, it is necessary to establish an appropriate data base against which to evaluate functional forms. Two paths might be followed. For developing a data base it is possible to use actual or bid costs of a suitable sample of projects, or to develop a series of cost estimates of hypothetical projects designed from scratch. Each approach has its own strengths and weaknesses. Utilizing actual project data has the advantage of encompassing in a suitable sample the range of conditions and factors found in practice. On the other hand, great care must be taken to insure that reported costs actually incorporate the full range of project expenses of interest and no others. In addition, there may be a number of project-specific factors which influence costs and add to unexplainable variance in the data set, thereby reducing the precision of estimated cost functions. A data set developed by synthetic costing techniques eliminates this type of random variation in the cost data, but in the process the assumptions and design philosophy of a single individual or group become imbedded in the data set. This may bias the data in ways which are not predictable a priori. In addition, synthetic cost studies may often miss cost areas which are important in real applications. For example, a recent synthetic cost study of sewage treatment plants produced estimating procedures which predicted costs substantially lower than those found in practice (EPA, 1976).

Given any particular data set, we find that cost functions may be developed by empirically fitting the data to arbitrary functional forms so as to produce a best fit by some criteria. Usually the techniques of linear or non-linear regression analysis are employed for this purpose. Alternatively, a particular functional form might be specified based upon the physical relationships of the variables in the system.

It is possible, and often desirable, to combine the approaches discussed above, but the existing cost studies have taken separate paths. Grigg and O'Hearn (1976) developed a cost function based upon a simplified model of the hydraulics of runoff and estimated the parameters of the model from synthetic costs developed for a single drainage area. Rawls and Knapp (1972) developed a data base of actual projects and fit a variety of linear and non-linear models to develop estimating equations. Functional forms were apparently chosen rather arbitrarily, in order to obtain the greatest explanatory power.

The Rawls and Knapp data base consisted of 70 projects from 23 areas located across the United States. The project data obtained included the design storm frequency (T) in years, average slope (S) in percent, runoff coefficient (C), number of inlets and manholes (M), smallest pipe diameter (D_B) in inches, largest diameter (D_E) in inches, outlet capacity (Q) in ft^3/sec, total length of drains (L_T) in feet, total drainage area (A_T) in acres, developed area (Ad) in acres, and total cost in 1963 dollars (C_T). The individual variables most highly correlated with the total costs were the total and developed drainage area, maximum pipe size, outlet capacity, length of drains, and number of inlets and manholes. For all of these variables $|r| > 0.5$. Noticeably absent from the data set were data on the magnitude of the design storm or soil characteristics, although these might be reflected to some extent in the other variables.

Rawls and Knapp estimated two primary types of cost models, and both were fit by nonlinear techniques. The first was a model designed for estimating costs from preliminary plans:

$$C_T = 58{,}273.0 + 8.73\,(T^{0.04} S^{-0.89} C^{0.64} D_B{}^{0.23} Q^{0.73} Ad^{0.71}),\ R^2 = 0.886 \quad (8\text{-}1)$$

The second model was for estimating costs from detailed designs:

$$C_T = 413 + 0.72\ L_T(D_B^{\ 0.92} + D_E^{\ 0.92}) - 39{,}640 + 31\ e^{0.01Ad},\ R^2 = 0.910 \qquad (8\text{-}2)$$

It should be noted that both models incorporate engineering design variables such as pipe size, maximum discharge, and number of manholes and inlets. Thus while these fits, as measured by R^2, are good, they are not appropriate for the planning level that we have in mind.

Rawls and Knapp also estimated simpler linear cost functions separately for observations from three separate states, and they found that they could explain a substantial proportion of the variation in costs in California and Texas. This result indicates that regional effects were important and might be related to the omission of rainfall and soil factors from the data base.

Grigg and O'Hearn developed a functional form for cost estimation from an idealized model of a single storm sewer draining a small basin. The following relations were employed:

Rational Formula: $$Q = CIA \qquad (8\text{-}3)$$

Manning's Formula: $$Q = \frac{1.49}{n} \left(\frac{D}{48}\right)^{2/3} S^{1/2} \left(\frac{\pi D^2}{4(144)}\right) \qquad (8\text{-}4)$$

rainfall intensity: $$I = \frac{KT^x}{t^b} \qquad (8\text{-}5)$$

and

pipe cost/ft: $$C_p = .0741\ D^{1.663} \text{ (from pipe cost data)} \qquad (8\text{-}6)$$

where T = design storm frequency, in years
n = Manning's roughness coefficient,
I = rainfall intensity, in inches/hour,
D = pipe diameter, in inches,
t = rainfall duration, in minutes,
C_p = pipe cost, in dollars/foot,
K, x, b = constants dependent upon region,

and other terms are as defined previously.

Combining these relations yields the cost expression:

$$C_p = 0.741\ a^{1.663} T^{0.624x} \qquad (8\text{-}7)$$

where $$a = 15.96 \left(\frac{nKCA}{t^b S^{1/2}}\right)^{.375} \qquad (8\text{-}8)$$

The final expression for total costs was determined by adding a factor for adjusting pipe costs to account for design, incidental costs, and other construction costs as a fraction of pipe costs (E) and a utilization factor, $u = U_0(1-e^{-\gamma T})$, expressing the fraction of maximum possible pipe length actually used in a given system. Thus:

$$C_T = (.0741)(1+E)(a^{1.663})T^{0.624x}(1-e^{-\gamma T})U_0 \tag{8-9}$$

The authors did not estimate the function for general topographic and rainfall conditions, but considered only a single site with different degrees of percent imperviousness and different design periods. They synthesized cost for drainage systems and fit these costs to functions of the design periods for each level of impervious area. Their final relationship was a simplified expression of the form:

$$C = a_i(1-e^{-0.18T}) \tag{8-10}$$

where a_i is a constant evaluated separately for each level of impervious area.

While the approach yielded good fits for the synthesized costs of the particular area under consideration, the adequacy of the general model (equations 8-3 to 8-6) for estimating costs for different areas, slopes, and design storms was not really evaluated.

REANALYSIS OF RAWLS AND KNAPP DATA

A model similar to that developed by Grigg and O'Hearn has been used to reevaluate the Rawls and Knapp data. This reanalysis has focused on developing a cost relationship suitable for preliminary analysis when no engineering data on pipe sizes, appurtenances, maximum discharge or pipe length are available. The model is outlined below:

Rational Formula: $$Q = CIA \tag{8-11}$$

General Flow Formula: $$Q = a_1 D^{a_2} S^{a_3} \tag{8-12}$$

Cost per unit length of pipe: $$C_p = b_1 D^{b_2} \tag{8-13}$$

System length: $$L_T = c_1 A^{c_2} \tag{8-14}$$

Combining these expressions yields:

$$C_p = b_1 \left(\frac{CIAS^{-a_3}}{a_1} \right)^{b_2/a_2} \tag{8-15}$$

and,

$$C_T = b_1 c_1 \left(\frac{CIAS^{-a_3}}{a_1} \right)^{b_2/a_2} A^{c_2} \qquad (8\text{-}16)$$

This expression can be multipled by a factor (1+E) to account for additional costs. Finally, a factor can be introduced to account for the degree of development in the drainage basin served. We will use the term $(A/Ad)^{c_3}$ which is the ratio of area served (A) to area developed (Ad). The parameter c_2 is assumed to be less than zero, since the larger the ratio the less extensive would be the pipe network required to serve a given area. The expression for total costs becomes:

$$C_T = (1+E) b_1 c_1 \left(\frac{CIAS^{-a_3}}{a_1} \right)^{b_2 a_2} \left(\frac{A}{Ad} \right)^{c_3} A^{c_2} \qquad (8\text{-}17)$$

which can be simplified to:

$$C_T = d_1 C^{d_2} I^{d_3} A^{d_4} S^{d_5} \left(\frac{A}{Ad} \right)^{d_6} \qquad (8\text{-}18)$$

where the d_i's represent the appropriate combinations of parameters and are to be estimated.

Examination of the derivation of the total cost equation leads to the following predictions about the signs of the parameters:

$$d_2, d_3, d_4 > 0 \qquad (8\text{-}19)$$

and

$$d_5, d_6 < 0 \qquad (8\text{-}20)$$

That is, costs should increase with increasing runoff coefficient, rainfall intensity, and drainage area and should decrease with increasing slope and ratio of total to developed drainage area.

A summary of the Rawls and Knapp data is presented in Table 8-1. One necessary variable, the design storm intensity, was not supplied directly by these data. Our initial approach was to replace this variable with an estimate: the 15-minute storm intensity, I_{15}, associated with the design frequency, T. The 15-minute interval was selected as being representative of the drainage basins in the data set. The 15-minute storm intensities are readily obtainable from historical records such as the graphs developed by Yarnell (1935). Planners should thus have relatively easy access to this information. A second, more accurate, measure of the design storm intensity, I, was inferred from the original data by using the figures on peak discharge,

TABLE 8-1. DATA SET SUMMARY, RAWLS AND KNAPP
(Number of Observations = 67*)

	Mean	Median	Standard Deviation	Hinges
Slope (%)	1.36	1.1	1.14	.4; 1.95
Runoff Coefficient	.49	.50	.086	.45; .5
Drainage area (acres)	119	59	211	36; 110
Total Cost (1963 $)	82,030	53,811	112,642	32,484; 86,795
Ratio of Total area to developed area	1.50	1	1.25	1; 1.46
15-minute storm Intensity (in/hr)	3.99	4.24	1.05	2.84; 5
Design Storm Intensity (in/hr)	3.63	2.95	3.3	1.75; 4.13
System Length (ft)	2,953	2,600	1,774	1,701; 3,574

*Three systems from the original data set are not included because of incomplete data.

runoff coefficient, and drainage area together with the rational formula, i.e., I = Q/CA. The implications of these alternative definitions of storm intensity area discussed subsequently.

The parameters d_1 to d_5 of equation (8-18) were estimated by taking the natural logarithms of both sides of the expression and using regression analysis on the resulting linear model. Results for this basic model are presented below:

$$\ln C_T = 7.86 - \underset{(.067)}{.134(\ln S)} + \underset{(.411)}{.764(\ln C)} + \underset{(.357)}{.530(\ln I_{15})} + .696(\ln A) - .356(\ln \frac{A}{Ad}) \quad (8\text{-}21)$$

$$R^2 = .571$$

$$S_e = .636$$

Number of observations = 67

where the numbers in parentheses are the standard errors of the coefficients. Taking the exponentials of both sides, the equation becomes

$$C_T = 2{,}594\, S^{-.134} C^{.764} I_{15}^{.530} A^{.696} \left(\frac{A}{Ad}\right)^{-.356} \quad (8\text{-}22)$$

This equation is in 1963 dollars. Using the ENR Construction Cost Index to update these costs to March 1977 requires multiplying by the ratio $(\frac{2513}{901}) = 2.79$.

All of the coefficients have signs predicted by the theoretical analysis, although only slope, area, and the ratio of total to developed area are significant at the five percent level. The standard error of estimate indicates that roughly 68 percent of model predictions should fall between 53 and 190 percent of the true value. Thus there is considerable unexplained variation remaining, which is not surprising given that the data are drawn from all parts of the country, and detailed design information has been omitted from the model.

The R^2 given is not directly comparable to the Rawls and Knapp values because it is computed on the log of the dependent variable. A comparable measure can be obtained by using actual and predicted cost values after a retransformation to the original form of the data. This value is $R^2 = .65$, which is still much lower than the Rawls and Knapp results. But with the exclusion of design information from the analysis, the results appear to be quite encouraging.

Another way of looking at the unexplained variation in the model is through the stem-and-leaf plot of residuals in Figure 8-1. The distribution is generally symmetric at about 0; there is one very extreme negative residual (model overpredicts) corresponding to a San Diego System.

We will now examine the implications of using the 15-minute storm instead of the actual design storm intensity. Recall that I_{15} was selected as an independent variable because it is fairly representative for the drainage areas of interest and can be obtained most directly by planners, since they do not need to know any detail about a particular drainage area.

In order to examine the potential effect of replacing I by I_{15}, we can look at a generalized intensity duration relationship (Butler, 1964):[1]

$$I = \frac{KT^x}{t^b} \qquad (8\text{-}23)$$

where T = design storm frequency (years),
t = storm duration (minutes) (generally equal to time of travel if rational method used)
K,x,b = parameters (usually location specific).

---

[1] This relationship has been presented previously; it is repeated here for the reader's convenience.

FIGURE 8-1. RESIDUALS FROM EQUATION 8-21

```
 1.4 |
 1.3 |
 1.2 | 2
 1.1 | 2
 1.0 | 02
  .9 | 9
  .8 | 523
  .7 |
  .6 | 77509
  .5 | 10
  .4 |
  .3 | 926
  .2 | 525923373
  .1 | 5509
  .0 | 693              Median = .03
 -.0 | 39               Hinges = -.30, .34
 -.1 | 686813
 -.2 | 2087470
 -.3 | 030
 -.4 | 172
 -.5 | 219
 -.6 | 9
 -.7 | 45
 -.8 | 913
 -.9 |
-1.0 |
-1.1 | 7
-1.2 |
-1.3 | 3
-1.4 |
-1.5 |
-1.6 |
-1.7 |
-1.8 |
-1.9 |
-2.0 | 0
```

Using this expression, the relationship between I and I_{15} for a constant design storm frequency is:

$$\frac{I_{15}}{I} = \left(\frac{15}{t}\right)^{a_3} \text{ or } I_{15} = I\left(\frac{15}{t}\right)^{a_3} \qquad (8\text{-}24)$$

Thus

$$\ln(I_{15}) = \ln(I) + a_3\ln(15) - a_3\ln t \qquad (8\text{-}25)$$

Two points about equation (8-25) are worth noting. First, t depends upon the slope and area, thus the use of I_{15} in place of I would mean that some of the slope and area effect in equation (8-18) would be incorporated into the intensity effect by the estimation procedure. Second, a_3 varies with location, so for the model estimated from national data it can be considered a random term. According to equation (8-25), this makes the independent variable I_{15} subject to random error, and as a consequence the estimated effect of the variable will be lessened relative to that of the true storm intensity (see Theil, 1971). The extent of this effect depends upon the variance introduced by a_3.

Improving the Estimate of I

In order to further examine the implications of this analysis, a second regression model was specified, this time using our estimate of the actual design storm intensity, I, in place of I_{15}. This procedure assumes that the outlet is designed only to handle the runoff from the design storm as predicted by the rational formula. The results of this regression are:

$$\begin{aligned}\ln C_T = 7.88 &- \underset{(.050)}{.158(\ln S)} + \underset{(.359)}{1.044(\ln C)} + \underset{(.113)}{.550(\ln I)} \\ &+ \underset{(.073)}{.774(\ln A)} - \underset{(.153)}{.411(\ln \tfrac{A}{Ad})}\end{aligned} \qquad (8\text{-}26)$$

$$R^2 = .680$$

$$S_e = .549$$

The inclusion of the more accurate estimate of I had the effect that our preceding analysis had suggested: each of the coefficients became larger in absolute value. In equation (8-26) all of the independent variables are statistically significant at the five percent level. Overall, there is a substantial improvement in the R^2 and a corresponding decrease in the standard error of the estimate compared with equation (8-21).

Since it appears that a more accurate estimate of the storm intensity contributes substantially to the predictive ability of the model, it is useful to consider how this additional piece of information could be made available at the planning level. One approach would be to compute travel time for representative classes of development types, slopes, and areas and present this data in graphical or tabular form. The planner could then use this information, together with design storm curves, to estimate a value for I in the cost equation.

Regressions on Cost/Foot

It is well known that the total cost of collection or distribution networks is heavily influenced by the length of the network. This variable has been ignored in the earlier regressions; in essence it was treated as a more detailed design parameter and the area variable used as a surrogate for length in the equations. However, in many types of developments utilities closely follow lot frontages, and fairly accurate rules of thumb are known for frontages associated with these developments. Therefore an alternative approach to equation (8-18) is to specify the dependent variable as cost per foot, C_p, in 1963 dollars. The basic model in equation (8-18) otherwise remains the same. The results of two regressions utilizing C_p as the dependent variable are reported below:

$$\ln C_p = \underset{}{1.559} - \underset{(.044)}{0.0944(\ln S)} + \underset{(.314)}{1.142(\ln C)} + \underset{(.099)}{.451(\ln I)} + \underset{(.063)}{.437(\ln A)} - \underset{(.134)}{.0524(\ln \frac{A}{Ad})} \qquad (8\text{-}27)$$

$$R^2 = .52$$

$$S_e = .480$$

$$\ln C_p = 1.528 - \underset{(.058)}{.0759(\ln S)} + \underset{(.353)}{.916(\ln C)} + \underset{(.307)}{.45(\ln I_{15})} + \underset{(.075)}{.372(\ln A)} - \underset{(.164)}{.0046(\ln \frac{A}{Ad})} \qquad (8\text{-}28)$$

$$R^2 = .37$$

$$S_e = .547$$

The two regressions differ only in the rainfall intensity term. I is used in equation (8-27); I_{15} in equation (8-28). While the explained variation (R^2) appears to be smaller than in the earlier regressions, this occurs only because the dependent variable has been defined differently. If, for example, values of $\ln C_p$ are computed for each observation using equation (8-27) and the log of length is added to each value, the resulting term is a predicted log of total costs.[2] The variation of these values can be divided by the total variation of these values can be divided by the total variation in $\log C_T$ to yield an R^2 comparable to the earlier regressions. The resulting value is .90, much higher than the earlier regressions and comparable to the detailed models of Rawls and Knapp. Thus considering cost on a per foot basis can result in substantially more accurate regressions, providing rules of thumb are accurate enough so that the system length will be known virtually without error.

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[2] $\ln(C_p) + \ln(\text{length}) = \ln(C_p \times \text{length}) = \ln(C_T)$

Evaluation of Predictions on Coefficients

According to the simple model upon which our analysis is based, the cost per foot should reduce to the following formula:

$$C_p = e_1(CIA)^{e_2} S^{e_3} \left(\frac{A}{Ad}\right)^{e_4} \qquad (8\text{-}29)$$

or

$$\ln C_p = \ln e_1 + e_2(\ln CIA) + e_3(\ln S) + e_4\left(\ln \frac{A}{Ad}\right). \qquad (8\text{-}30)$$

Thus the relationship predicts that the same coefficient should apply to the variables C, I, and A. This prediction was tested by running a regression for equation (8-30):

$$\ln C_p = 1.0823 + \underset{(.0576)}{.431(\ln CIA)} - \underset{(.0492)}{.094(\ln S)} - \underset{(.134)}{.0594\left(\ln \frac{A}{Ad}\right)} \qquad (8\text{-}31)$$

$$R^2 = .478$$

$$S_e = .493$$

Despite the constraints imposed in equation (8-31), the R^2 is not much less than the comparable R^2 in equation (8-27), where C, I, and A were allowed to take on separate coefficients. The reduction in R^2 is not significant at a five percent level, nor are the coefficients for S and $\frac{A}{Ad}$ changed much. These results further support the validity of the underlying conceptual model.

Regional Effects

A number of site or region specific factors may influence the collection system cost. For example, soil characteristics, in so far as they influence the costs of installing pipe, could be an important factor aside from their influence on the value of C. Then too, there may be systematic differences in engineering practice or the nature of design storms used in different parts of the country. The published data did not permit a detailed evaluation of these influences. However, we have attempted to introduce some control for these influences by introducing dummy variables designating region of the country. Using census definitions, the cities in the data set were assigned to one South, West or North (Northeast and North Central). One example of the analysis is given by equation (8-32), which represents an extension of equation (8-26) incorporating regional effects as dummy independent variables:

$$\ln C_T = 7.560 + \underset{(.40)}{.782}(\ln C) + \underset{(.12)}{.504}(\ln I) + \underset{(.073)}{.766}(\ln A) - \underset{(.057)}{.141}(\ln S)$$

$$- \underset{(.17)}{.452}\left(\ln \frac{A}{Ad}\right) + \underset{(.187)}{.286}(D_s) + \underset{(.238)}{.293}(D_w) \qquad (8\text{-}32)$$

$$R^2 = .693$$

$$S_e = .547$$

where D_s = dummy variable for South, 1 if city is in South, 0 otherwise.

D_w = dummy variable for West, 1 if city is in West, 0 otherwise.

These results can be interpreted to say that total costs were $e^{.286}$ = 1.33 higher in the South than the North and $e^{.293}$ = 1.34 higher in the West than the North, all other factors being equal. Nevertheless, neither of the two dummy variable coefficients are significant at a five percent level, nor does equation (8-32) result in statistically significant improvement in R^2 over equation (8-36) at a five percent level. Thus the analysis does not support the existence of a regional effect. This does not mean that the factors discussed above are unimportant, although that is one possible interpretation. Since the regionalization was very crude, it may easily have blurred important distinctions between areas, and therefore the lack of statistical significance may be due to the lack of precision in the variables.

Use of Regression Equations

The analysis up to this point has focused on explaining the variation in costs for a readily available sample of drainage systems. The results suggest that relatively simple models can be developed for predicting conventional collection costs, but the use of the specific equations estimated here must be approached with some caution. If the sample used is not representative of the types of systems for which we wish to predict costs, equations based on the sample are likely to give imprecise or possibly biased estimates of costs. In order to see whether such limitations are important for this data set, we have examined predictions from our estimated equations against independently reached estimates for a typical low density subdivision in the Boston area. In addition, we have compared descriptive statistics on the sample to characteristics of typical new subdivisions.

Costs in the Boston area--

A typical low-density subdivision in the Boston area might have the following characteristics:

area = 50 acres
lot size = 1 acre
length of pipe = 4000 feet
slope = 5 percent
runoff coefficient = .25
design storm = 5.5 inches/hour

According to design data from our consultant, BSC Engineering, the costs for the storm sewer system would be approximately $60,000. We can compare this figure with the following predictions where costs have been adjusted to March 1977:

equation (8-21) $C_T = 75{,}927$
equation (8-26) $C_T = 70{,}967$
equation (8-27) $C_T = 111{,}570$
equation (8-28) $C_T = 118{,}007$
equation (8-31) $C_T = 175{,}332$
equation (8-32) $C_T = 68{,}243$

The models generally over-predict total costs, although the range is considerable. In this specific case equations (8-21), (8-26) and (8-32), which are based on total cost, are better predictors than the equations estimated on a cost per foot basis, despite the fact that the latter fit the sample data much more successfully.

Table 8-2 compares descriptive statistics on selected variables in the sample, with values which would be typical of new, small residential subdivisions in the Boston area. This table shows that there are substantial differences between the two sets of numbers. Slopes in the sample tend to be flatter than typical Boston area values and the runoff coefficients are high relative to values for single family home developments, although more typical of higher density uses such as townhouses. It is particularly interesting to look at the drainage density and cost per foot figures. Systems in the sample utilize less pipe per acre of land but with higher unit costs than the new subdivisions. This result suggests that many of the systems in the sample represent parts of interconnected collection systems, whereas many new subdivisions at the urban fringe have independent collection systems for stormwater. That is, each system handles runoff for the specific subdivision, not for upstream users, and discharges either to a watercourse or large trunk lines. There are, of course, other explanations for the differences as well. If many of the sample systems were existing built-up areas, then the cost of line installation would be much greater than when land is first developed. Whatever the reason, it is apparent that our caution in using the estimated regressions for predicting new subdivision costs is well founded. Given the differences between the sample and the subdivisions of interest, it is evident that predictions based on these regressions involve extrapolations which tend to magnify the estimation errors of the models even if the specifications themselves are perfectly appropriate. The results of the cost comparison also suggest that the simple equations (8-21) and (8-26) may be more resistant to the problem than the models which rely on more detailed information, but it is impossible to make any generalization based upon this single cost comparison.

ADAPTING COST FUNCTIONS FOR NON-CONVENTIONAL MANAGEMENT SYSTEMS

The cost functions developed for conventional collection systems can be extended to handle certain kinds of additional management options. These options include systems which either add an additional cost component to the system and/or directly impact one of the underlying variables in the equation.

TABLE 8-2. COMPARISON OF DRAINAGE AREA CHARACTERISTICS

	Sample Values Median	Sample Values Hinges	Typical values: Boston area Developments*
Slope (%)	1.1	.4; 1.95	1-10
Runoff Coef.	.5	.45; .50	.25 SF (large lot) .5 Townhouse .75 Apt.
Drainage Area (acres)	64	36; 110	30-200
Drainage System density (ft/acre)	54	36-83	80-200
cost/ft (March 1977 dollars)	60	50; 78	15-20

*BSC Engineering, Inc.

The use of a storage basin to serve the entire subdivision is an example of the first case. In this case it can be assumed that the role of the collection system is unaffected and that the final pipe in the subdivision discharges to the basin. Thus the cost function would be written:

$$C_S = C_T\ (C,I,A,Ad,S) + C_B \qquad (8\text{-}33)$$

where C_T is the total collection cost function discussed previously and C_B is the cost of providing a storage basin.

This cost can vary widely depending upon the nature of the site, the value of land, and the design of the storage system. Benjes (1976) and Sullivan, et al., (1977) have presented cost functions for stormwater storage facilities which relate capital cost to the storage volume of the facility. However. the types of facilities covered in these studies are for metropolitan scale management, not for small subdivisions. Engineering Science, Inc. (1973) has developed cost estimates for sedimentation basins that are probably more representative of the simplest types of storage facilities that might be constructed. These costs are related to the size of an earth dam and outlet structure of specific dimensions, not directly to volume of the facility. By making specific assumptions about the slope and other characteristics of the site, however, it is possible to convert these costs to functions of storage volume.

Increased on-site infiltration is an example of a management system which affects the underlying variables in the collection cost function. A simple technique of this type is the discharging of the roof gutters to the lawn rather than to the driveway or collection system. This would appear as a decrease in the value of C for the cost equation and would reflect a decrease in the maximum size of pipes in the collection system. For example, according to equation (8-26), a reduction of ten percent in the runoff coefficient would result in approximately the same percentage reduction in total costs.

Stormwater management measures that fundamentally change the type of transport system, for example, by using swales in place of sewers, could not be treated as simply as the previous two cases. While the basic conceptual analysis that underlies equations (8-11) to (8-18) would still apply, specific equations estimated from data on conventional systems would be inapplicable. A new set of cost data would be needed to estimate functions similar in form to those for the conventional system.

SECTION 9

INSTITUTIONAL AND POLITICAL ISSUES

INTRODUCTION

While the technical problems in stormwater management may be formidable, the ultimate challenge may yet prove to be that of implementing proposed solutions at a local level. Most of the measures being considered as options for on-site control of stormwater are, by their nature, different from methods generally practiced. Implementing these measures will therefore require that local governments and regulatory agencies alter standard procedures and require new types of information and cooperation from developers. Since any change involves a certain risk, there will be some understandable reluctance on the part of these governments to make changes. This reluctance may be further enhanced by pressures from groups that feel threatened by changes in the existing procedures. In this section we examine the possible difficulties that can arise in introducing innovative stormwater management measures.

REGULATORY SYSTEMS AFFECTING INNOVATION IN RESIDENTIAL DEVELOPMENTS

There is not much experience in introducing innovative stormwater control measures at a local government level. As a consequence, it is not possible to draw generalized conclusions about difficulties that may be encountered and ways of overcoming such difficulties from the limited number of examples that currently exist. Therefore, the first approach taken in this study was to examine the pertinent literature on similar innovations in residential development for which there is more extensive experience. Two types of innovations were selected: the introduction of Planned Unit Development (PUD) regulations in zoning and subdivision ordinances; and the modification of building codes to allow innovative construction techniques. Both of these examples resemble the stormwater case in key respects: they are tied to the process of developing new residential subdivisions; their responsibility rests almost exclusively with local boards and agencies; and they represent examples of innovations which, proponents argue, promise substantial benefits for the "general public." There is also a more direct connection: PUD ordinances allow the possibility of using residential development layouts to manage stormwater (see Section 6).

By examining the studies of innovation in zoning subdivision and building codes, it is possible to develop a general appreciation for the local factors that will influence the acceptance of stormwater control measures and how these factors may vary according to geographical location, socio-economic differences, and other considerations. This discussion can then be used as a general background against which the two case studies that follow can be assessed. These studies involve subdivisions featuring innovative stormwater management plans designed by BSC Engineering Inc. In both cases towns in southeastern Massachusetts accepted the plans only after considerable difficulty.

PLANNED UNIT DEVELOPMENT REGULATIONS

Planned unit developments (PUD) are large scale residential developments which cluster housing on part of the site, leaving part for open space. These developments are a fairly recent innovation in site design. They allow the developer to minimize utility costs and in some cases, to mix the types of housing provided. Zoning and subdivision regulations are the main tools used by government to guide development including PUDs. Regulations specifically aimed at PUD have developed from these two traditions. We will start with an overview of zoning and subdivision regulations and then discuss PUDs in more detail.

According to the National Commission on Urban Problems (NCUP), every state has enabling legislation which allows the use of zoning and subdivision regulations, and more than 10,000 local governments have adopted them (1968). A survey conducted in 1968 showed that 90 percent of all cities and towns with populations over 5,000 had zoning ordinances, and 83 percent had subdiviison regulations (Manvel, 1968). These regulations were first widely used in the 1920s and still reflect patterns established at that time, but they have been tailored to meet the objectives of each local government.

A zoning ordinance typically assigns a use category such as residential or industrial to a geographic area, establishes maximum allowable density, regulates building bulk, and includes a zoning map which establishes districts of uniform uses. It is administered by a self-executing, non-discretionary permit process which also provides for zoning appeals for variances and for amendments for rezoning. Significant differences exist among various regions of the country in the distribution of zoning powers among levels of government (NCUP, 1969). In the West, Midwest and South both counties and municipalities have zoning powers. This is also true in some northeastern states, but in the six New England states the counties have no zoning powers.

Density limitations, usually expressed as minimum lot sizes, are particularly inflexible aspects of zoning ordinances. The 1968 survey showed that 94 percent of governments with zoning regulations had minimum lot size provisions. Over one-fifth prohibited lots of less than one-quarter acre. New England townships are stricter; over fifty percent disallowed less than quarter acre lots (Manvel, 1968).

A typical subdivision regulation covers site design and relationships, insures that utilities tie into those of adjoining property, allocates costs of public facilities such as sewers, and sometimes provides for dedication of land for schools or parks. It is administered through the provision of general design standards which are applied by the local planning commission or governing body to preliminary and final plans submitted by the developer. Subdivision approval is a bargaining process between the municipality and the developer. Standards frequently established include width and alignment of streets, dimensional requirements for lots, street grading and paving requirements, standards for curbs, gutters, drainage and sidewalks, and utility systems. Subdivision control is generally more flexible than zoning and involves negotiations on each separate tract. Since subdivision control relates to vacant land, counties play a larger administrative role than with zoning, particularly for unincorporated territory. However, municipalities also exercise this authority, frequently with extra-territorial control.

Both zoning and subdivision regulations are characterized by local responsibility. While state enabling legislation is required, they reflect local policies administered by local officials. They presuppose land development on a small scale, lot-by-lot, and are structured for administrative convenience, zoning to prevent change in established neighborhoods and subdivision control to protect the public interest in servicing land to be developed in the future. In discussing the failure of the local approach to planning to promote coordinated land use, Lamb (1975) observed that local government structures lead to ad hoc decision making based upon immediate political, economic and social pressures. In addition, local officials may be major landowners themselves or be highly dependent on campaign contributions from large property holders, and thus have an interest in preserving the status quo.

Recent changes which have occurred in these regulations have included a widespread reduction in permitted residential density, an increase in the number of subjects regulated (for example, landscaping), and innovative administrative changes that allow the locality to adopt a wait and see approach (as opposed to self-executing standards) leaving the initiative to the developer. The planned unit development or PUD is an example of this change in administration which has only been widely adopted since 1963.

The PUD technique applies requirements to an entire project rather than on a lot-by-lot basis. It also requires discretionary public review of site plans proposed by the developer, sometimes combining zoning and subdivision control into a single process. Approval of a planned unit development depends on the fulfillment of certain conditions. These generally include minimum size, permitted uses, maximum density, provision of open space and public facilities and maintenance of control of the area during and after development. Implementation of PUDs usually occurs through zoning amendments which require legislative action, through approval of special permits by the board of adjustment, or through planning commission authority to approve special exceptions or conditional uses; local provisions vary widely.

In 1968 the National Commission on Urban Problems reported that 45 percent of localities with zoning ordinances provided for specialized treatment of PUDs (Manvel, 1968). As of 1973, six states (New Jersey, Pennsylvania, Connecticut, Kansas, Colorado and Nevada) had enacted PUD enabling laws based on the Model Act published in 1965 by the Urban Land Institute and the National Association of Homebuilders (Bangs, 1973). Six other states had included PUD-like techniques in their planning and zoning enabling legislation.

A 1971 survey conducted by Burchell indicated that PUD projects tend to be located in states with high urban growth and those with specialized climate or topographic conditions conducive to recreation housing (Burchell, 1972). Burchell attempted to relate the existence of municipal PUD ordinances and developer inquiries regarding PUD with various socio-economic characteristics. He was unable to determine any significant relationships other than the availability of sufficient vacant land to accommodate large-scale projects and the use of a municipal planning consultant. Burchell concluded that a significant portion of the variation in incidence of PUD legislation enactment was unexplained by the study and could probably be attributed to the variation in sophistication of local officials and in developer promotional ability.

Sophisticated approaches such as PUDs require sophisticated administrators. Many urban fringe jurisdictions which are experiencing development pressures do not have adequate staff to handle large scale development. The typical reaction of local governments such as these is either to defer to the developer, to impose traditional unsophisticated controls or to try to prevent development completely.

Jan Krasnowiecki, a leading theoretician of land use law, indicates that there is a growing tendency in PUD ordinances to limit permissible densities to the same level as permissible under applicable standard zoning because municipalities are afraid that PUD represents growth (Krasnowiecki, 1973). He also feels that an increasing amount of detail is beginning to find its way back into PUD ordinances, so that a developer may be turned down for a "legitimate" reason or so that he must build very expensive housing. This conclusion is supported in Table 9-1 which shows the results of an American Society of Planning Officials study of PUD ordinances. Local officials are not comfortable with the resonsibility of a negotiated project, and many do not have the necessary professional staff, so they prefer to rely on ordinance provisions.

In discussing the problems encountered by large-scale developments, the Urban Land Institute ranks high the conflicts and uncertainties caused by public agency regulations (Urban Land Institute, 1977). In many localities, developers must proceed through a maze of regulations with different officials reviewing the plan for street layout, sanitary facilities, building location, etc. Often the process of obtaining permits turns into prolonged negotiations involving considerable uncertainty as to the final standards to be imposed on the project. Delays and uncertainty have major cost implications including extended loan payments and higher interest rates due to increased risk. As stated by the National Commission on Urban Problems, "Institutional delays are not uncommon in communities which prefer no development at all and the disapproval of a single official, perhaps on personal whim, can destroy the proposal entirely or set it back for months. Even where PUD is theoretically available to developers, some prefer to build conventional subdivisions solely to avoid the added dangers and burdens which administrative processing can

TABLE 9-1. ORDINANCE DESIGN STANDARDS FOR PUDs

Design Elements	Percent of Ordinances With Specific Standards
Uses permitted	79.0
Density	77.8
Minimum parcel size	92.6
Usable public open space	46.9
Private open space	33.3
Maximum site coverage	51.9
Building spacing	44.4
Building bulk and height	46.9
Building architecture	4.9
Location of window walls	7.4
Quantity of parking spaces	74.1
Location of parking spaces	24.7
Perimeter requirements	34.6
School and recreation site dedication	25.9
Streets and utilities	48.1
Landscaping	33.3
Signs and street lighting	35.8
Screening and fencing	38.3
View protection	16.0

Source: So, Mosena, and Bangs, 1973.

impose." (NCUP, 1968, p. 227). This statement is supported by a survey conducted by the American Society of Planning Officials of 300 members of the National Association of Home Builders concerning the PUD review process. In comparing the processing time for PUD developments with conventional subdivisions, 69 percent of those responding felt that PUD developments were significantly slower (ASPO, 1973).

As one developer was quoted as saying, "Some agencies make procedural requirements so complex that only the most determined developer would attempt to go the PUD route." (ASPO, 1973, p. 14)

The following case examples will illustrate this point more fully.

In 1968, a developer proposed a PUD for an area of a New Jersey township zoned for one-half acre single family residences (House and Home, 1971). The proposed development included mutli-family dwellings and commercial and office buildings. The town planning board rejected the plan because the higher density did not appeal to them, nor did the concept of preservation of open land, which the board viewed as a tax loss. So the developer decided to apply for a conventional single family development. However, many objections were raised since the town, in fact, wanted no new development at all. The developer went to court and finally got approval for the single family subdivision. At that point the town decided that it wanted a PUD after all. So a PUD ordinance had to be passed which took six months and involved numerous public meetings to explain the concept. After the ordinance was approved, it took another year involving negotiations concerning tax revenues, school loads, road layout, and provision of utilities, for the final plan to be approved. At least four years were spent on the whole process.

In 1965, a cluster development was proposed in a small town fifty miles from Manhattan (Raymond and May Associates, 1968). The proposed plan had lot sizes half the size of the zoning ordinance requirement but designated half the site for open space. It had a central sewage system and less road mileage than a conventional development. Town law permits the town board to authorize the planning board to modify the zoning ordinance to permit this type of development. Townspeople were hostile to any form of development, especially homeowners adjacent to the site who were afraid that the smaller lot sizes would attract undesirables. The town board rejected the proposal on the basis that the reduction in lot sizes did not meet the general character of the area. The developer countered by submitting a conventional grid system plan meeting the zoning regulations. This was rejected by the planning board partially on the basis of the lack of a central sewage system, even though there were no regulations requiring such a system. Just prior to the decision a new planning board member had been appointed who was an adjacent homeowner and an opponent of development on the site. The developer took the decision to court but lost his case.

BUILDING CODE REGULATIONS

A building code is a set of specifications designed to establish minimum safeguards in the erection and construction of buildings. It is a checklist that a unit or structure must satisfy before it is approved for construction. Codes have been used since colonial times; today almost every community has one in force. Manvel found that 80 percent of all cities and towns of over 5,000 population have building codes (1968). Like zoning ordinances, building codes are formulated and enforced through the police powers of state governments which have traditionally been delegated to and exercised by local governments.

The typical building code is composed of three parts: definition of terms; licensing requirements; and standards. Each code defines key work areas such as what constitutes plumbing work, and authorizes, through licensing requirements, who is to do what work. These provisions serve to guarantee certain work for certain groups such as building trade unions.

Building codes are based on standards which are technical specifications that determine whether a product, subsystem or complete housing system meets minimum requirements for health and safety. Most standards specify how an element of a housing unit must be built rather than how it should perform. If a new technology does not conform to the specifications of the standard, it cannot be approved, even if its performance is better. Some codes contain "equivalency" clauses which allow the local code enforcement official to determine if a material or process is of equivalent quality to that specified in the standard. However, this determination is generally difficult for a local official because of lack of technical knowledge and experience.

Product standards are developed by the various building trade associations representing specialized product groups such as the Cast Iron Pipe Institute or the National Forest Products Association. One cause of the lack of performance standards is the resistance of product manufacturers to establish standards that open the market to newcomers.

Standards are incorporated into local codes through direct lobbying by industry representatives at the local level or through one of the model code associations. There are four major model code groups for the building construction industry, each generally drawing membership from one region of the country. The Building Officials' Conference of America (BOCA) (Basic Building Code) dominates in the Northeast, the International Conference of Building Officals (ICBO) (Uniform Building Code) in the West, and the Southern Building Codes Conference (SBCC) (Southern Standard Building Code) in the South. Both BOCA and ICBO compete for city members in the North Central region. The National Building Code, published by the

American Insurance Association, has been adopted by 1600 communities in all regions of the country except the West. The first three model code groups are associations of building officials. In the West and South over the past fifteen years, regional model codes have been generally adopted by all municipalities (Falk, 1973). In other areas of the country, there is more variation among localities.

The building official insures that the building code standards are met. He is responsible for approving building plans, inspecting construction of buildings and issuing permits of occupancy. As mentioned above, he generally has special approval power over new technologies. Local building code officials are not well paid and frequently lack technical training, job security and on-going educational opportunities. Most officials come out of the local construction industry. These factors tend to make them conservative toward new technologies and building code reform (Field and Rivkin, 1975).

There are also other reasons why local control of building codes has had adverse consequences for the acceptance of new technologies. The lack of a uniform set of substantive requirements means either that separate designs must be prepared for each locality or that the product must meet the most stringent local requirements, both of which cause cost increases. Sometimes local enforcement causes an inspection problem. For example, sophisticated production techniques used closed wall construction which cannot be visually inspected. In reaction, local ordinances may ban manufactured housing entirely or require the producer to remove the walls off the site, nullifying any cost saving.

Furthermore, as mentioned earlier, most building codes are written in specification terms rather than performance terms so that a new technology which does not conform to the specifications cannot be approved. Any radical innovation, such as housing manufacturing or industrialization, which affects major portions of the housing unit is resisted if it means loss of jobs or sales to subcontracting firms or individuals. In addition, when a material producer proposes changes that affect other firms in the industry, for example, the plastic industry's proposed use of plastic pipe in place of cast iron pipe, resistance appears. Building codes are a part of this resistance because, as discussed above, their standards are developed by building trade associations and their provisions are influenced by lobbying by industry representatives. Through the efforts of building supply manufacturers, dealers and building trade unions, certain specific technologies (e.g., plastic pipe) have been specifically prohibited by some locally enacted codes.

The 1968 National Commission on Urban Problems survey investigated the effect of building codes on fourteen building characteristics or components which involved building practices that resulted from recent technological developments. Most of the practices considered were acceptable under the four regional model codes (Manvel, 1968). The survey showed that one practice was outlawed by over 60 percent of all governments with building codes, four were outlawed by over one-third, three by one-quarter, and two by one-fifth, while the other four showed a smaller percentage of prohibition. Very little difference in prohibition was observed between those governments whose codes were reported to be based on regional models and those with locally developed codes.

Thus the establishment of model codes for local adoption has not resolved the problem of uniformity across municipalities even though model codes are revised from time to time to accept new products and methods. Most localities do not adopt a model code without substantial amendments, and furthermore, many localities do not adopt the periodic revisions without several years delay. The National Commission on Urban Problems study results showed that only 15 percent of all municipalities and New England-type townships with a population greater than 5,000 had in effect a national model building code which was reasonably up to date (NCUP, 1968). The rest used their own code or one based on a state code, failed to keep their model code up to date or had no code. In addition, local inspectors often interpret the code in a manner which differs from the language of the model code and from interpretations of the identical language by inspectors in neighboring localities.

Field and Rivkin, in their book The Building Code Burden, (1975) analyze in detail the effects of building codes on market aggregation and on innovation, and relate them to certain parameters such as the vitality of the construction industry and the form of lcoal government.

They report the results of a second study made of the same 14 innovative building practices studied by the National Commission on Urban Problems (see p. 9-15). Each city was scored in terms of the number of code prohibitions among the 14 items. Locally-based codes were more prohibitive than those based on model or state codes, although many items were still specifically prohibited even in the latter cities. Code revision indicates progressiveness; the more recent the code revision, the less prohibitive the code. Again communities with locally based codes were the least likely to be current. A high proportion of the largest cities used locally drafted rather than model codes. Field and Rivkin suggest that this pattern occurs for two reasons: 1) model codes do not typically cover high rise construction; and 2) local interest groups such as unions and subcontractors use stronger influence where a higher volume of construction is at stake. On a national basis, the older, more industrial sections of the country were more likely to use locally drafted codes since steady or declining construction activity probably encourages efforts to preserve local jobs and sales. Thus the younger, generally faster growing western and southern regions tended to adopt model codes, whereas the slower growing northeast and north central regions had a greater incidence of locally drafted codes.

Since market aggregation is important for the growth of innovative building technologies such as manufactured housing, Field and Rivkin aggregated the data from their study of the 14 innovative building technologies to create state-level code prohibition scores. The highest prohibition scores occurred in areas where locally-based codes were more common, the mid-atlantic states, the Midwest, and the northern Midwest. Variation in code provisions from community to community reflects localism, the degree to which decision making takes place within the community and subject to its influences. Field and Rivkin rated states according to the degree of within-state dissimilarity in acceptance of the 14 innovative items. The regions of least dissimilarity were the west and central plains states. Generally, the more industrial the states, the stronger the local construction industry and the greater its influence on local code design. Also, the ICBO code association appeared to be a strong influence in the West. City government form may influence the degree of localism. The city manager form of government is prevalent in the West and the professional orientation of city managers may make them more willing to accept the ICBO code association recommendations. The mayoral form of government is more common in the South and North, perhaps reflecting local attitudes toward professionalism in government. Further analysis of this data combined with information from a 1970 study of housing manufacturers indicated that the restrictiveness of codes was related to the vitality of the construction industry and to the extent to which political influence could be exerted on local building officials. Slow growing cities with mayoral forms of government had the most restrictive codes; city manager cities had the least restrictive codes.

The discussion so far has examined the widespread problem of restrictive local building codes. It is instructive to review an example of federal involvement in an attempt to modify this regulatory system. In 1969 the Department of Housing and Urban Development initiated Operation Breakthrough. One of its objectives was to develop ways to overcome the perceived constraints of local building codes on the growth of the manufactured housing industry which uses innovative technology and requires national markets. The strategy selected was to encourage state legislation authorizing statewide regulation of manufactured housing which would pre-empt locally enacted building codes under the states' police power. When the program was announced, no states had mandatory state-wide building code regulatory systems applicable to all forms of manufactured housing. In 1973 there were 28 states with such laws, primarily in the West, Northeast and Southeast (Falk, 1973). The greatest degree of uniformity among state standards exists in the West, and the West also has the beginning of a centralized approval system for new technologies. Those which are accepted by the ICBO Research Committee are also acceptable by regulation in some states and carry weight in other states. Thus is the West, the prerequisites for an aggregate regional market have developed. The situation is not as favorable in other regions of the country. Attempts to achieve reciprocity or uniformity of substantive requirements between states have not been successful. Thus Operation Breakthrough has created statewide markets for manufactured housing, but not a national market.

SUMMARY OF LITERATURE REVIEW

The regulatory systems which we have reviewed hinder the application of innovative technologies in the residential construction industry. Although regulations are, of course, necessary to preserve the health, welfare and environment of a community, their substance and administration vary widely. Certain factors appear to influence the degree to which these regulations inhibit innovation. These are summarized here. These same factors are likely to influence the regulation of techniques to control stormwater runoff.

Growth Rate

A fast growing area provides a fertile market for the building industry. If there is plenty of work, then there is less need to restrict newcomers to the market, so innovations are less likely to be resisted.

Community Attitude Toward Growth

A "no growth" or "slow growth" community will attempt to use the regulatory system to keep new development out or to raise costs in order to increase the tax base.

Influence of Project Manufacturers and Unions

Because of the way the building industry is structured, with many interrelated firms and individuals, and because these groups have access to the regulation development process, they tend to have a strong conservative influence on regulations which can be used to maintain their sales and jobs. Innovations which do not disrupt their positions will be easier to implement. This factor is related to the first, since an expanding economy will ease the pressure to maintain a market share, while a contracting one will increase the pressure.

Degree of Professionalism in Government

The degree of professionalism in government is likely to affect both the content and administration of regulations. The more professional government will turn to national models for the design of its regulations. Such a government will also be less likely to allow personal interest or political favors to interfere with regulation administration.

City Size

This factor is important, as it relates to the first factor, since a large city may have more work available and therefore more permissive regulations. A larger city is also more likely to have an adequate staff with the technical expertise to administer sophisticated regulations. However, a large city, especially one located in an older industrial area of the country, may be slow growing and therefore exacerbate the problems caused by competition among firms.

Local Regulatory Officials

The experience, training, interests, and attitudes of the local regulatory officials determine to a large extent the acceptability of innovative techniques, since these individuals play such an important role in the existing regulatory process.

Geography

In the East and North, regulations seem to be more restrictive, while in the Midwest, South and West, less so. Rural areas by definition are the least developed and therefore likely not to have constraining regulations, although when faced with development may apply unsophisticated controls. Suburban areas around major metropolitan centers are likely to be under the most pressure and therefore be the most restrictive.

It is important to note that the factors identified above are not strictly separable. For example, western municipalities in the surveys cited tend to be faster growing, have a more positive attitude toward growth, and are often regarded as having greater professionalism in government than northeastern cities. Similarly, southern cities are faster growing and are less influenced by strong unions than northeastern cities. Thus it is not appropriate to identify a specific effect with a single factor; the casual linkages are far too complex. It is clear however, that there is considerable variation among municipalities in their acceptance of innovation in the residential development and construction industry, and that this variation is at at least partially explained by a number of community characteristics.

Without exception, it is anticipated that the factors discussed will bear on municipalities' acceptance of innovations in stormwater management. Like building codes, new management techniques will require that municipalities take a more flexible approach in the implementation of technical standards and may entail the replacement of existing products, thereby displacing some local suppliers and labor. Like PUD ordinances, some stormwater control measures would require consideration of the layout of the tract as a whole rather than a lot-by-lot approach and would require flexibility in subdivision standards for road pavements, curbing and other elements. Thus if past experience in these related areas is any guide, there will be considerable difficulty in obtaining acceptance of new stormwater management concepts. Our two case studies describe the types of difficulties that did arise in two towns. These are relatively rural communities in southeastern Massachusetts. Both tend to be "slow growth" in outlook and have small government organizations with little in the way of specialized technical expertise. Thus we would predict a priori that they would be highly resistant to new innovations.

CASE STUDIES[1]

The two case studies describe the process of gaining acceptance of innovative drainage and roadway designs for two residential developments in Southeastern Massachusetts. Both developments are located in affluent bedroom suburbs of Boston, have similar populations, lie within the coastal plain of Massachusetts Bay and share the same vehicular corridor to Boston. Despite these similarities, they provide an interesting comparison since their sites have completely different geomorphological characteristics and

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[1] This subsection is based on a document prepared by BSC Engineering Inc. under subcontract to Meta Systems Inc.

and the communities in which they are located have contrasting land-use regulatory systems.

Trout Farm--

Trout Farm is a unique residential development of clustered homes in Duxbury, Massachusetts. It was the first project to receive full approval under Duxbury's innovative Impact Zoning Ordinance which was adopted in 1973. This zoning by-law permits almost complete flexibility in design of the development. Density is negotiated under a ceiling of two dwelling units per acre, depending on the proposal's sensitivity to the site constraints and off-site socio-economic impacts.

The ordinance was the by-product of a comprehensive community planning exercise which included the development of a socio-economic model of the community. This model is used to weigh additional housing demands versus available community infrastructure capacity. Site development features, housing types, bedroom mixes and housing densities are compared to their projected impacts. Tax revenue/services costs (benefit/cost) analysis is made for the project and becomes a part of the approval process for a proposed development.

Under the Duxbury Protective Zoning By-Law, the approval process requires submission of plans at three stages and concurrent review at each stage by all municipal agencies. The multi-agency review/negotiation period specified in the by-law includes a 60-day approval period for a special permit and is designed to be completed in less than a year.

Geomorphology--The 42 acre Trout Farm site is a white pine forest with little forest understory. The site is roughly divided by a small groundwater fed stream of very high quality which discharges to a small, shallow cranberry bog reservoir no longer in agricultural use. The valley of the stream is covered by wild fields with a mixed succession of soft and hardwood trees and shrubs reclaiming the once cleared fields.

The soils are exceptionally well drained glacial outwash deposits. Depth to the groundwater table ranges from zero at the brook to greater than 20 feet near some residences. The soils generally are classified as Merrimac sandy loam and Carver coarse sand under the USDA Soil Conservation Service classification system. They are highly permeable soils with permeabilities in excess of 6 inches per hour. Actual percolation tests in carefully constructed test holes with adjacent observation trenches showed percolation rates of 30-45 seconds per inch with a roughly 1 horizontal to 5 vertical gradient through the unsaturated soils and a saturated gradient (slope of the phreatic surface) of .01-.03 ft./ft.

Because of the sensitive nature of the brook -- a stream of two- to three-foot width and six-inch depth, primarily groundwater fed -- and the characteristics of the soils, it was decided to design a completely infiltrative drainage system. The objective was to increase the infiltration characteristics of the site by developing it. The approved plan allows for 105 dwelling units of various types, bedroom counts and ownership arrangements. Generally, the housing is set in the higher wooded areas of the site and the lower elevation fields and stream are preserved as common open space. All the roadways have a stabilized stone surface and all the roofs are piped through downspouts to leaching pits. Other than the roof leaders there are no drainage structures, pipes or outfalls anywhere in the project. The history of the site plan approval was as follows:

- Late in 1973 the first stage was completed. Preliminary Qualification and Site Analysis submissions were presented and preliminary approval was received to proceed with the Tentative Plan submission.
- Planning for the site was carried out and the complex graphic and text submission required for the second approval stage was prepared. The Tentative Plan for a special permit exception was submitted on June 4, 1974.
- Based upon initial comments during review meetings, supplemental text and graphics were prepared and submitted on July 29, 1974. This text nearly equaled the initial submission.
- A public hearing was held at the High School Auditorium on August 29, 1974 and the special permit exception issued on November 26, 1974, nearly six months after submission -- not two months as specified in the by-law.
- The permit provided general conditions on which the project could proceed. These conditions set forth further planning requirements to be approved prior to preparation of the final SITE PLAN. Studies and meetings continued, and on May 27, 1975 an amended special permit was issued.
- During this time the housing market was deteriorating. Market acceptance of condominiums was particularly poor, and it was decided to modify the design by changing most of the attached housing to a "zero-lot line" clustered subdivision. The physical layout of units remained essentially the same except lot lines were drawn through the party-walls of attached units. This change greatly enhanced the market acceptance of the units, even though the lots were small and restricted to their natural pine needle cover.
- On March 5, 1976 the final site plans were submitted and reviewed by agencies and their consultants.
- Final permits were issued in May of 1976, nearly three years after the beginning of planning.
- Sewage disposal permits and curb opening approvals were not issued until October of 1976.

The process, which was intended to take less than a year, actually lasted almost three years. Why did the delays occur in the streamlined multi-agency review and one-stop permit process? Clearly, since this was the first proposal to go through the process, some slowness due to inexperience was to be expected.

The multi-agency nature of the review process itself, however, caused certain difficulties. At each stage, the submitted plans were distributed to all the local boards and, in turn, to their consultants for review. The planning board included both a planner and an engineer; the board of health had an engineer and also forwarded plans to a state agency for comments; the water department had a consultant; the conservation commission included engineers and hydrologists; and other boards did their own review. As one might expect due to the number of people involved, many of the review comments conflicted with each other and negotiations were required to resolve the various opinions. These negotiations did not concern housing density and infrastructure demand as envisioned in the town ordinance. For example, a lively debate took place between the town board of health and the state environmental agency. Frequently, the developer had to take a mediating role in order to keep the permit approval process moving. In addition the uniqueness of the roadway was a source of considerable concern, particularly from engineering consultants with a more conservative or traditional point of view. Questions asked repeatedly were, "Where have you done this before?" or "Can you prove it will work over time?" What finally won the approval of the infiltrative roadways were not technical arguments but the design of a politically satisfactory package in which granting approval would not make existing residents liable for future maintenance or repair costs for the roadway. This will be discussed further below.

Bowker Woods--

The Bowker Woods project in Norwell is a conventional subdivision in which the homes are clustered on oversized lots. The zoning in Norwell permits only conventional subdivisions of single-family detached residences on one-acre lots. Lots must have 150 feet minimum width at the building setback line and a shape which permits the enclosure of a 150-foot diameter circle in which the house and septic system must be placed. No wetland area in any lot can be counted toward the minimum one-acre lot area.

All new roads in Norwell must have a right-of-way depth of 50 feet and meet strict horizontal and vertical alignment criteria. The pavement width must be 26 feet and must have curbs and 5-foot sidewalks on each side. Minimum permissible water main size is ten inches. Pavement section requirements are as follows: 1 1/2 inch bituminous concrete top course; 3 1/2 inch bituminous concrete binder course; .05 gal/sy MC 700 tack coat; 12-inch gravel base course -- 95 percent compaction; 23-inch non-frost susceptible material -- 97% compaction.

Geomorphology--The 36-acre Bowker Woods site was a former wood lot for a box-mill and had been nearly completely cut-over during the early part of this century. A strong second growth of mixed deciduous trees occupies the steeply sloping upland areas. The site is rather gently sloping along an old wood road, but rises sharply to the north and west with slopes over 25 percent. The southeast corner and a significant part of the parcel's frontage are upland red maple swamp.

The steeper portions of the site are very dense stony till deposits or dense silty till deposits with high groundwater levels. In fact, groundwater seeps from the surface of the ground during the spring. The wetlands areas are unsuitable for development. Only the narrow band of land along the old woods road contains some ice-contact deposits of permeable soils. The SCS soil classifications of the till deposits are Essex -- very stony coarse sandy loam, Norwell -- extremely stony sandy loam, and Gloucester -- very stony find sandy loam. The glacial retreat deposits are Brockton and Merrimac sandy loams with permeabilities in the six inches per hour range.

The parcel fronts on an existing public way, Bowker Street -- a designated historic way. It has very poor vertical and horizontal alignment, narrow (16-ft) pavement width, small culverts with little or no cover, and no drainage. Ice and frost conditions in winter require the highway department to make the road one-way. However, residents have no desire to change its character because it controls traffic speeds and maintains the town's original country flavor.

Prior to the involvement of BSC Engineering Inc. in early 1974, a 27-lot conventional subdivision planned by others had been proposed for the Bowker Woods area. This proposal was denied because of adverse impact on the site. Planning was begun by BSC Engineering for a 19-lot development with a unique roadway design which required relief from some of the town's road construction standards. This resubmission in October 1974 also was not viewed favorably primarily due to sewage disposal considerations. A detailed soil investigation was then conducted to determine the soil characteristics and their suitability for on-site sewage disposal systems. This study indicated that the site was severely constrained from a geological standpoint.

The area of suitable soils was mapped and the regulated setback from the wetlands was plotted to determine the net buildable area in terms of sewage disposal systems. It appeared that the developer could reasonably expect to receive ten sewage disposal permits, since approximately ten lots could be placed on suitable soils.

Ten was also the number of lots which could be located on the site if it were simply divided while meeting the town zoning requirements and fronting on Bowker Street. The planning board could not legally deny such a proposal. Because of these considerations, it was possible to use the ten-lot number to negotiate for significant waivers in lot configuration and roadway standards. The planning board agreed to allow gerrymandering of the lot boundaries and a narrow, ecologically sensitive roadway design generally following an old cart path, as long as the developer agreed to go through a detailed subdivision review process which otherwise would not have been required. The ten-lot development plan was approved on October 27, 1975.

Municipal Financial Risk Considerations

In both Duxbury and Norwell town officials showed concern regarding the future performance of the unique roadway designs included in the two development proposals. BSC Engineering had not designed or built such a road previously, nor had a similar installation been developed by others in the area. Thus adequate performance could not be proved from past experience.

The approach used to gain approval for the new roadway designs was to be open about their experimental nature and to request that town officials become part of this advance in technology. However, care was taken to insure that neither elected officials nor other residents of the community would risk any future public expenditures.

In both Trout Farm and Bowker Woods the roadway right-of-way geometry meets town standards. However, the ways are private and their maintenance cost is borne by the homeowners in the development. Therefore, if in the future the roads completely failed, requiring the towns to take action, no land-taking would be required. Furthermore, if reconstruction were required at some point, betterments would be charged to the abutting homeowners, thereby passing on to them road construction charges that would have been included in the cost of their lots had a more traditional roadway design been used initially.

In both cases during the negotiation period, BSC Engineering illustrated how the roadways could be converted to more conventional street designs completely within the dedicated private ways. In Trout Farm catch basins and leaching pits could provide drainage for an impervious surface. In Bowker Woods, where the soils do not permit total leaching disposal, conventional basin and pipe design was demonstrated which discharged to a retention pond, and outlet structures were designed assuming an impervious roadway of conventional width. The public was granted rights of access to the retention pond.

These agreements concerning future financial risk and the discussions regarding alternative roadway designs were all part of the public record. Their validity is upheld by the covenants placed upon the land and in the language in the homeowners' association agreement.

REASONS FOR PROJECT SUCCESS

As noted in the first part of this section, many innovative developments are discouraged or abandoned when faced with complex and lengthy approval processes. The two projects that have been described in the case studies managed to endure through such processes as well as through a severe economic decline. Residential developments were produced which were different from any others in their communities. What was unique about these projects, their developers and the municipalities which permitted success? Following are some of the major reasons for their uniqueness:

- The developers in both instances were known in their communities. The Trout Farm owners are a group of local businessmen who have other sources of income and who had a strong desire to do something creative. The Bowker Woods developer is an old Boston real estate firm with an excellent reputation that had the ability and willingness to continue through all of the negotiation and approval steps required.

- The developers owned the properties outright and were not under time pressure to obtain the approvals and close on the property.
- Local officials and municipal agency personnel wanted to see something creative done and were willing to risk the political consequences if the projects turned out poorly and became a source of complaints and ridicule.
- The high-income nature of the developments meant that the developers could afford to do proper planning.
- The developers had a reputable planning team that was willing to do some unusual design work.

APPENDIX A

ANALYSIS OF LOADING AND WASHOFF DATA

INTRODUCTION

Two basic strategies adopted in gathering data for use in quantifying urban stormwater pollutant loadings are discussed below. One strategy has concentrated on measuring the accumulation and composition of dust and dirt on street surfaces. Street accumulation measurements have been taken to provide bases for evaluating street sweeper effectiveness and for calibrating the accumulation/washoff functions typically included in various urban runoff models. These studies are plagued by the difficulties involved in estimating deposition rates from street solids measurements in the presence of a variety of wet- and dry-weather deposition and removal mechanisms. Uniform sampling and data reduction procedures for measuring street solids have not been defined. Further, both pollutant loadings scoured from off-street surfaces during rainstorms and possible non-conservative behavior of some pollutants in stormwater collection and transportation systems are ignored when street solids measurements are used to estimate loadings to urban waterways.

The second strategy is essentially end-of-pipe sampling. Measurements of flow and concentration provide the basis for estimation of loadings. Difficulties are associated with the temporal variability of flow and concentration typical of urban storm events. Such variability can cause sampling, measurement, and data interpretation problems. Possible seasonal or longer-term effects suggest that such studies should be carried out for long periods to provide a basis for estimating characteristic loadings.

BRIEF DISCUSSION OF PREVIOUS STUDIES

Currently, the most widely quoted and applied study on accumulation rates of solids and associated pollutants on street surfaces is that performed in 1974 by URS Research Company (URS, 1974). Their results have been published in at least three forms (URS, 1974; Singh, 1977; and Bradford, 1977) and have been adopted by authors of various manuals dealing with methodologies for urban runoff assessment (McElroy, et al., 1976). The URS study consisted of compilation and analysis of existing data (as of 1974) on street solids accumulation rates and composition. The data were drawn primarily from four studies -- APWA, 1969; AVCO, 1970; and URS, 1972 -- and are listed in the 1974 URS reports.

A total of seven "independent" variables were considered: climate (region); land use; average daily traffic, type of landscaping beyond sidewalks; type of street surface; days since last rain; and days since last sweeping. "Dependent" variables included solids loading rate (lbs/curb-mile/day) and solids composition (micrograms/gram), comprising a total of 16 constituents and 153 observations.

The authors anticipated and observed a great deal of variance in solids loading rates and composition within each independent variable category. This variance was attributed to "natural" variability and to differences in sample collection and analysis methodologies. The latter factor was undoubtedly important, especially because of the methods used to aggregate samples, and because, although most of the observations were based upon street accumulation measurements, some were based upon direct runoff measurements. The analysis was also hindered by missing values and by collinearity in the independent variables.

The data were grouped according to independent variable categories, and averages and standard errors were computed for each group. For each dependent variable t-tests were employed to test for significant differences between each sub-group and the overall data set. In a formal statistical sense these tests were not done properly, since in each case the data from the tested group were contained in both populations being compared. The tests should probably have been done between each group and the remaining data. Also, the comparisons are incomplete: t-tests to consider whether two population means differ assume that the means are drawn from a distribution with a common variance; there were no checks made to see if this was in fact the case. Failing this, the t-tests can tell us little about the differences in population means. In fact, we might expect the sub-population variances from different land use categories to be different, and there is a wide range in the sample variances that URS presented.

EXPLORATORY DATA ANALYSIS

The exploratory process partially relieves us of the burden of having a specific explanatory model of the data at hand. Thus we start with a display of the data. As described in Section 5, the graphical technique used is called a stem-and-leaf display (Tukey, 1977). The basic purpose of such displays is to arrange raw data into roughly numerical order -- like a histogram -- so that one can easily answer questions such as: what is the largest value? the smallest? what does the distribution of values look like? Unlike a histogram, however, the display retains some of the identity of the original data by using the actual digits of the data values to construct the display. This makes it easier to see which data value is located where in the histogram.

How then do we construct the display? We first scan the list of the original data (see Figure A-1) to determine a suitable scale for the values. In this case units of tens seem appropriate. Taking the first data value, 400 lbs/curb-mile/day (112.7 kilograms/curb-kilometer/day), we cut it to units of tens (the ones place is truncated). Four hundred becomes 40 (tens). Next, 40 is separated into two parts: the right-most digit, 0 and the rest, 4. The 0 part is called the leaf (because it projects from the left-hand side), and the 4 is called the stem. We show the separation of the stem from the leaf by drawing a vertical line between them -- 4**|0; the asterisks indicate that there are really two digits in the leaf (400 really could become 4|00), but we show only one of them -- the tens digit. The display is built by placing the stems on the left and the leaves on the right; Figure A-2 shows the step-by-step construction of the display. At each step the number placed into the display is marked with an arrow. The next data value is 600; it becomes 6**|0, and its placement on the display is shown by Step 2 of Figure A-2. Value 390 becomes 3**|9 (Step 3), 210 becomes 2**|1, 170 becomes 1**|7, 19 becomes 0**|1, and so forth. Data value 32 appears on the same line as data value 19 and becomes 0**|13.

FIGURE A-1. RAW DATA: RESIDENTIAL LOADING RATES
(LBS/CURB-MILE/DAY)
(URS, 1974)

400	600	390	210	170	019	032
121	148	081	062	121	135	148
019	020	096	153	060	022	
032	035	024	033	041	028	
070	092	2700	690	260	860	
220	372	659	418	70	85	24
77	238	18	34	103	93	40
770	950	205	950	100	67	93
33	11	8	3	295	31	165
13	69	17	27	18	6	8
39	45	22	12			

Number of observations = 71

FIGURE A-2. STEPS IN CONSTRUCTING STEM-AND-LEAF DISPLAY

```
   Step 1          Step 2          Step 3          Step 10

6**|            6**|0 ←         6**|0           6**|0
5  |            5  |            5  |            5  |
4**|0 ←         4**|0           4**|0           4**|0
3  |            3  |            3  |9 ←         3  |9
2**|            2**|            2**|            2**|1
1  |            1  |            1  |            1  |247
0**|            0**|            0**|            0**|138 ←

   (value          (value          (value          (value
placed = 400)   placed = 600)   placed = 390)   placed = 081)
```

When there are too many values to fit on one line, stems can be separated. As an example, we could have one stem for leaves 0, 1, 2, 3, and 4 and the other for 5, 6, 7, 8, and 9. If we were to do this for the data points represented by 0**|138, we would have:

```
   .|8 .
 0**|13
```

Working through all the data points leads to a complete stem-and-leaf presentation (Figure A-3).

As discussed in Section 5, log-transformations lead to improved representations. Thus, Figures A-4 through A-11 show the stem-and-leaf displays of the distribution of loadings for the constituents Pb, cadmium, organic nitrogen, orthophosphate (O-PO_4), and nitrate. Exceptions to the log-normal pattern are usually found where the sample size is small (less than 20); this is to be expected from statistical considerations. In most cases log-transformations do a good job of making the data more symmetrical. We can conclude from this that the reported mean values and standard deviations are not good values to use for summarizing loading rates. Use of log-transforms is suggested, along with medians.

ANALYSIS BY TWO-WAY TABLES

The model described above assumes that the processes that account for the observed loading on streets are numerous and otherwise unanalyzable; that is, a black box. To continue the exploratory analysis, we specify a set of factors that we presume contribute to the final loading level. Other researchers have attempted to specify such categories as land use or perhaps traffic density as intuitively plausible factors; we would expect industrial and commercial land to have patterns of accumulation that differ from low-density residential. Nevertheless, it may well be that other factors, including a generally high "residual" variability, may mask these effects. This was found to be the case in the URS study: high variability within categories -- as measured via t-tests -- hampered the attempt to distinguish differences in accumulation among land use categories. As we have seen, this is due in part to the use of raw data; log-transformed values do not behave quite so badly. Another approach is to use medians instead of a least squares analysis because medians are insensitive to extreme fluctuations in the data. To perform the analysis, we disaggregate the data into a model of the form:

```
LOADING = common value            + land use effect
          (over all categories)   + traffic effect
                                  + climate effect
                                  + residual
```

where the residual is a normally distributed source of error. We are in effect making the categories into "dummy variables."

The first step in applying the technique is to find the effect of being in a particular land use -- for example, across all climates (Table A-1). For residential land uses only, what is the typical loading? For this row the typical value as represented by the median is $(1.70 + 1.59)/2 = 1.65$. Similarly, the commercial, light industry, and industry row medians are 1.61, 1.98, and 1.76, respectively. Proceeding, we subtract the row medians from each of the data values to obtain a new table (Table A-2). Just as with land uses, we now find the climate fit, only this time we naturally look down each column.

FIGURE A-3. RESIDENTIAL LOADING RATES
(LBS/CURB-MILE/DAY)
(URS, 1974)

```
loading rate x 100
          |
     27** | 0    Milwaukee
          |
          |
          |
     10** |
          | 55
      9   |
          | 6
      8   |
          | 7
      7   |
          | 95
      6   | 0
          |
      5   |
          |
      4   | 01
          | 97
      3   |
          | 69
      2   | 1230
          | 756
      1   | 2423400
          | 8696797879696
      0** | 1312233234221342100311210034 21
          |
```

Number of observations = 71

Results:

upper hinge:	205	(57.80 kg/curb-km-day)
median:	70	(19.74 kg/curb-km-day)
lower hinge:	27	(7.61)
spread:	178	(46.52)

Note:

median:	the data value half-way in from either end; half the data lies above, or below this data point.
hinge:	upper (lower) -- half-way from the high (low) data extreme to the median, i.e., one-quarter of the way in from either end.
spread:	difference between upper and lower hinges, i.e., contains one-half of the data.

FIGURE A-4. LN (RESIDENTIAL LEAD LOADING, MICROGRAMS/GRAM)
(URS, 1974)

```
                 loading x 0.01

                   .  | 6
                   8  | 12120
                   .  | 9767666988
                   7**| 335035034304
                   .  | 77686898
                   6  | 44310541
                   .  | 868
                   5**| 43
                   .  | 79
                   4  | 1
                   .  |
                   3**|
                   .  | 8
                   2  |
                   .  |
                   1**|
                                  upper hinge= 7.60
   n=53                                median= 7.00
                                  lower hinge= 6.35
```

FIGURE A-5. LN (RESIDENTIAL NO_3 LOADING, MICROGRAMS/GRAM)
(URS, 1974)

```
                 loading x 0.01

                      |
                      |
                  10**|
                   .  |
                   9  | 3             <(Lawrence, Mass.)
                   .  |
                   8**|
                   .  | 9
                   7  |
                   .  | 68678
                   6**| 4042205221
                   .  | 798
                   5  |
                   .  |
                   4**|
                                  upper hinge= 6.70
   n=20                                median= 6.30
                                  lower hinge= 6.00
```

FIGURE A-6. RESIDENTIAL CADMIUM LOADING (MICROGRAM/GRAM)
(URS, 1974)

```
                 loading x 0.1

                   8 |088

                   7 |2

                   6 |001

                   5 |2455

                   4 |0235

                   3 |01345556

                   2 |03456778

                   1 |0111334667

                   0 |000034678
   n= 50                          upper hinge = 4.3
                                       median = 2.7
                                  lower hinge = 1.1
```

FIGURE A-7. LN (COMMERCIAL ORTHOPHOSPHATE LOADING MICROGRAMS/GRAM)

```
                 loading x 0.01

                      |
                   5  |
                   4**| 20
                   3  | 9274
                   2**| 9733
                   1  |
                  +0**| 583
                  -0  | 9
                  -1**| 3
   n=15               |
                                  upper hinge= 3.70
                                       median= 2.70
                                  lower hinge= 0.50
```

FIGURE A-8. LN (COMMERCIAL LEAD LOADING, MICROGRAMS/GRAM)
(URS, 1974)

```
        loading x 0.01
             |
             |
      7**    |
       .     |
      6      |
       .     |
      5**    |
       .     |
      4      | 30
       .     | 5559658
      3**    | 430001
       .     | 75
      2      |
       .     |
      1**    |
n=17         |
                       upper hinge= 3.70
                            median= 3.50
                       Lower hinge= 3.00
```

FIGURE A-9. LOG (COMMERCIAL NITRATE LOADING, MICROGRAMS/GRAMS)
(URS, 1974)

```
        loading x 0.01
             |
      2**    |
       .     | 6
      1**    | 4222403
       .     | 565677
      0**    |

n=14

                       upper hinge= 1.35
                            median= 1.10
                       lower hinge= 0.60
```

FIGURE A-10. LN (INDUSTRY AND LIGHT INDUSTRY COD LOADING, MICROGRAMS/GRAM)
(URS, 1974)

```
        loading x 0.01

      6**    |
      5      | 34415
      4**    | 20
      3      | 148
      2**    | 8
      1      |
      0**    |
n=11

                       upper hinge= 5.35
                            median= 4.20
                       lower hinge= 3.60
```

FIGURE A-11. LN (INDUSTRY AND LIGHT INDUSTRY LEAD LOADING, MICROGRAMS/GRAM)
(URS, 1974)

```
        loading x 0.01

      8**    | 1
       .     | 968965
      7      | 0020324
       .     | 686
      6**    | 14
       .     | 857
      5      |
       .     |
      4**    | 1
       .     | 8
      3      |
       .     |
      2**    |
n=24

                       upper hinge= 7.60
                            median= 7.00
                       lower hinge= 6.10
```

For a particular climate, what is the typical value? (This time we are not using the original data values, but those with land use effects subtracted out.) In Table A-2 notice that we also find the median of all land use effects themselves by looking down the column labelled "Row Median." This is the "median of the row medians" -- the overall loading common to all land uses and climates. Again, we subtract the column medians from the respective table values above them and subtract the overall effect from each of the row medians (Table A-3).

TABLE A-1. LOG-TRANSFORMED LOADING DATA

Land Use	Climatic Region Northeast	Southeast	Northwest	Southwest	Row Median
residential	2.13	1.70	1.59	1.43	1.65
commercial	2.01	1.61	1.20	1.61	1.61
light industry	2.13	2.02	1.77	1.93	1.98
industry	2.71	1.64	1.59	1.87	1.76

TABLE A-2. TRANSFORMED LOADING DATA MINUS ROW MEDIAN

Land Use	Climatic Region Northeast	Southeast	Northwest	Southwest	Row Median
residential	0.48	0.05	-0.06	-0.22	1.65
commercial	0.40	0	-0.41	0	1.61
light industry	0.15	0.04	-0.21	-0.05	1.98
industry	0.95	-0.12	-0.17	0.11	1.76
column medians	0.440	0.020	-0.190	-0.025	1.705 Overall Value

If we had used means as typical values, we would now be done; however, since we are using medians the process is not quite complete. If we now calculate row medians, we see they are not quite zero; this indicates that we should go through the whole process once more, but this time "polishing" the fits by subtracting only the new, small row medians. We must then do the same for the column medians. We repeat, moving from polishing rows to columns until the medians for both are relatively (within round-off error) close to zero. We are left, in this case after four steps, with row effects along the right-hand side, column effects along the bottom, and the common, overall value in the lower right-hand corner (Table A-4). What numbers are left in the cells? Those not accounted for by climate, land use, or overall value -- the residuals.

TABLE A-3. TRANSFORMED LOADING DATA WITH ROW AND COLUMN MEDIANS SUBTRACTED

Land Use	Climatic Region Northeast	Southeast	Northwest	Southwest	Row Fit	Row Median
residential	0.040	0.030	0.130	-0.195	-0.055	0.035
commercial	-0.040	-0.020	-0.220	0.025	-0.095	-0.030
light industry	-0.290	0.020	-0.020	-0.025	0.275	0
industry	0.51	-0.140	0.020	0.135	0.055	0.078
Column Fit	0.440	0.020	-0.190	-0.025	1.705 Common Value	-0.003

TABLE A-4. LOG (MEDIAN SUSPENDED SOLIDS LOADING, LBS/CURB-MILE/DAY) LAND USE VERSUS CLIMATIC REGION (URS, 1974)

Original Data

Land Use	Region Northeast	Southeast	Northwest	Southwest	Row Median
residential	2.13	1.70	1.59	1.43	1.65
commercial	2.01	1.61	1.20	1.61	1.61
light industry	2.13	2.02	1.77	1.93	1.98
industry	2.71	1.64	1.59	1.87	1.76

The Two-Way Fit: Loading = Common Value+ Land Use (row) Effect + Region (column) Effect + Residual

					Row Effect
residential	0.01	-0.01	0.13	-0.25	-0.08
commercial	-0.01	0.01	-0.15	0.04	-0.18
light industry	-0.29	0.02	0.02	-0.04	0.22
industry	0.43	-0.22	-0.02	0.04	0.07
Column Effect	0.44	0.03	-0.23	-0.01	1.76 Common Value

Tables A-5 through A-10 give the results of the two-way table analysis as applied to a series of comparisons between landscaping, climatic region, land use, and traffic density for various constituents along with a stem-and-leaf display of the residuals for each analysis. The results are discussed in Section 5 of the main text. Following the tables are the diagnostic plots for all of the two-way tables, Figures A-12 to A-20. These attempt to uncover possible non-linear interactions between the factors analyzed in the corresponding table; the results are discussed in Section 5 of the main text.

TABLE A-5. TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LANDSCAPING VERSUS CLIMATIC REGION (URS, 1974)

Original Data

	Landscaping				
Climatic Region	grass	trees	landscaped buildings	none	row median
Northeast	2.714	1.672	2.170	2.182	2.176
Southeast	1.833	1.519	1.544	1.778	1.661
Southwest	1.431	absent	absent	1.371	1.401
Northwest	1.484	absent	1.455	1.204	1.455

The Fit

	Landscaping				
Climatic Region	grass	trees	landscaped buildings	none	row effect
Northeast	0.450	-0.131	0.000	-0.005	0.604
Southeast	-0.016	0.131	-0.211	0.006	0.189
Southwest	-0.013	absent	absent	0.004	-0.216
Northwest	0.013	absent	0.078	-0.190	-0.189
column effect	0.097	-0.364	0.003	-0.020	1.563 (common value)

Residuals x 1000

```
 4** |5
  .  |
 3   |
  .  |
 2** |
  .  |
 1   |3
  .  |7
 0** |0010101
-1   |3
  .  |9                   upper hinge= 0.04
-2** |1       n=13             median= 0.00
-3   |                    lower hinge=-0.07
```

TABLE A-6. TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LAND USE VERSUS LANDSCAPING (URS, 1974)

Original Data

	Landscaping				
Land Use	grass	trees	landscaped buildings	none	row median
Residential	1.842	1.512	2.130	2.029	1.936
Commercial	1.505	1.613	1.398	1.415	1.460
All Industrial	2.493	absent	absent	1.869	2.181

The Fit

	Landscaping				
Land Use	grass	trees	landscaped buildings	none	row effect
Residential	-0.139	-0.288	0.128	0.138	0.0
Commercial	0.000	0.289	-0.128	0.000	-0.476
All Industrial	0.267	absent	absent	-0.267	0.245
column effect	0.045	-0.136	0.066	-0.045	1.936 (common value)

Residuals x 1000

```
   3   |
   2** |86
   1   |23
   0** |00
  -1   |32
  -2** |86
  -3   |                upper hinge= 0.130
            n=10             median= 0.0
                        lower hinge=-0.130
```

TABLE A-7. TWO-WAY FIT, LN (MEDIAN COD, MICROGRAMS/GRAM X 0.001) CLIMATIC REGION VERSUS LAND USE (URS, 1974)

Original Data

Climatic Region	Land Use Residential	 Commercial	 All Industrial	Row median
Northeast	3.56	6.13	3.22	3.56
Southeast	4.87	3.00	2.89	3.00
Southwest	4.14	4.82	5.36	4.82
Northwest	3.64	absent	absent	3.64

The Fit

Climatic Region	Land Use Residential	 Commercial	 All Industrial	Row effect
Northeast	0.0	2.57	0	-0.04
Southeast	1.87	0	-0.45	-0.60
Southwest	-0.68	0	0.20	1.22
Northwest	0	absent	absent	0.04
column effect	0	0	-0.34	3.60 (common value)

Residuals x 100

```
  3** |
    . | 5
    2 |
    . | 8
  1** |
    . | 2
   +0 | 00000
    . | 6
 -0** | 4
      |         upper hinge= 0.20
          n=10       median= 0.0
                lower hinge=-0.0
```

TABLE A-8. TWO-WAY FIT, LN (MEDIAN COD, MICROGRAMS/GRAM X 0.001) LAND USE VERSUS AVERAGE DAILY TRAFFIC VOLUME (ADT) (URS, 1974)

Original Data

Land Use	Traffic Volume less than 500	500-5000	5000-15000	greater than 15000	row median
Residential	absent	3.820	3.951	3.469	3.820
Commercial	absent	5.509	6.020	3.211	5.509
All Industrial	5.403	absent	4.151	absent	4.777

The Fit

Land Use	Traffic Volume less than 500	500-5000	5000-15000	greater than 15000	row effect
Residential	absent	0.00	0.000	0.974	-0.294
Commercial	absent	0.00	0.380	-0.974	1.395
All Industrial	0.00	absent	-0.094	absent	0
column effect	1.223	-0.066	0.065	¯1.390	4.180 (common value)

Residuals x 100

```
 10 |
  9 |  7
  8 |
  7 |
  6 |
  5 |
  4 |
  3 |  8
  2 |
  1 |
 0**|  0000
 -1 |  9
  2 |
  3 |                upper hinge  0.19
 -4 |         n=8        median= 0.00
  5 |                lower hinge=-0.05
  6 |
  7 |
  8 |
  9 |  7
-10 |
```

TABLE A-9. TWO-WAY FIT, LN (MEDIAN LEAD, MICROGRAMS/GRAM X 0.1) LAND USE VERSUS CLIMATIC REGION (URS, 1974)

Original Data

	Climatic Region			
Land Use	**Northeast**	**Southeast**	**Southwest**	**row median**
Residential	4.394	4.443	5.416	4.443
Commercial	4.277	5.416	5.298	5.298
All Industrial	3.497	4.543	4.927	4.543

The Fit

	Climatic Region			
Land Use	**Northeast**	**Southeast**	**Southwest**	**row effect**
Residential	0.383	-0.589	0.00	.489
Commercial	0.0	0.118	-0.384	0.755
Industrial	-0.025	0.00	0.00	0.00
column effect	-1.021	0.00	0.384	4.543 (common value)

Residuals x 1000

```
 3** |8
 2   |
 1** |1
+0   |0000
-0   |2
-1** |
-2   |
-3** |8
-4   |
-5** |8

                   upper hinge= 0.059
          n=9           median= 0.0
                   lower hinge=-0.205
```

TABLE A-10. TWO-WAY FIT, LN (MEDIAN LEAD, MICROGRAMS/GRAM X 0.1) LAND USE VERSUS AVERAGE DAILY TRAFFIC VOLUME (URS, 1974)

Original Data

Land Use	Average Daily Traffic Volume (ADT) less than 500	500-5000	5000-15000	greater than 15000	row median
Residential	4.284	4.575	4.369	absent	4.369
Commercial	absent	5.687	5.966	5.371	5.687
All Industrial	4.060	4.431	5.247	4.787	4.609

The Fit

Land Use	Average Daily Traffic Volume (ADT) less than 500	500-5000	5000-15000	greater than 15000	row median
Residential	0.147	0.000	-0.485	absent	-0.069
Commercial	absent	0.000	0.000	-0.229	1.043
All Industrial	-0.146	-0.213	0.324	0.230	0.000
COLUMN EFFECT	-0.403	0.035	0.314	-0.052	4.609 (common value)

Residuals x 1000

```
  4** |
  3   |2
  2** |3
  1   |4
  0** |000
 -1   |4
 -2** |12
 -3   |
  4** |8
                  upper hinge= 0.140
           n=10        median= 0.0
                  lower hinge=-0.210
```

FIGURE A-12. DIAGNOSTIC PLOT, RESIDUALS FROM TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LAND USE VERSUS CLIMATIC REGION

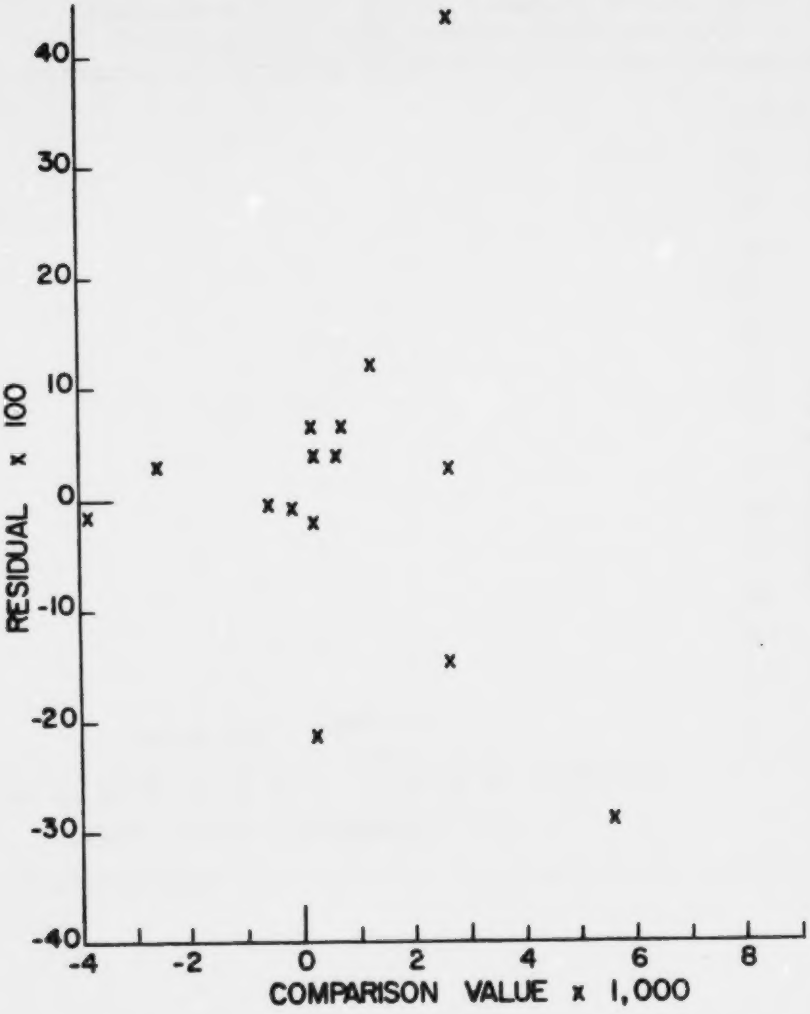


FIGURE A-13. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LAND USE VERSUS AVERAGE DAILY TRAFFIC VOLUME

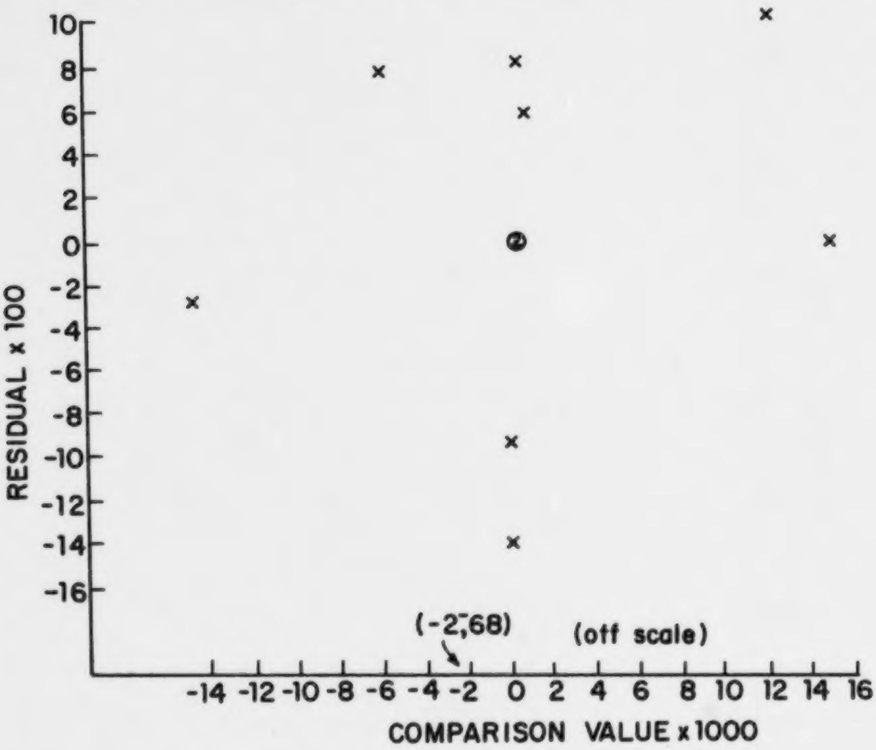


FIGURE A-14. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LANDSCAPING VERSUS AVERAGE DAILY TRAFFIC VOLUME

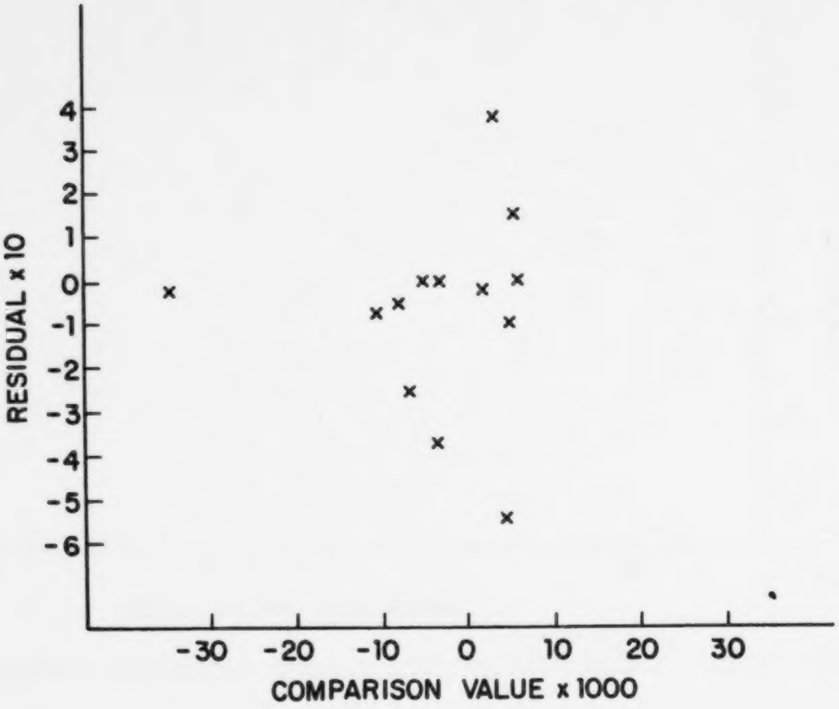


FIGURE A-15. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT,
LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY)
LANDSCAPING VERSUS CLIMATIC REGION

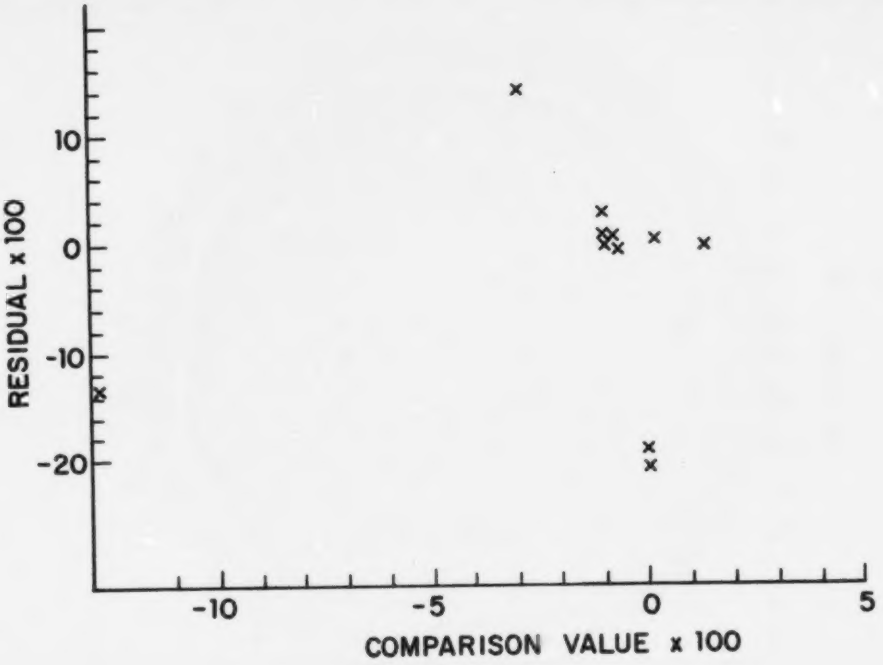


FIGURE A-16. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT, LOG (MEDIAN SUSPENDED SOLIDS, LBS/CURB-MILE/DAY) LAND USE VERSUS LANDSCAPING

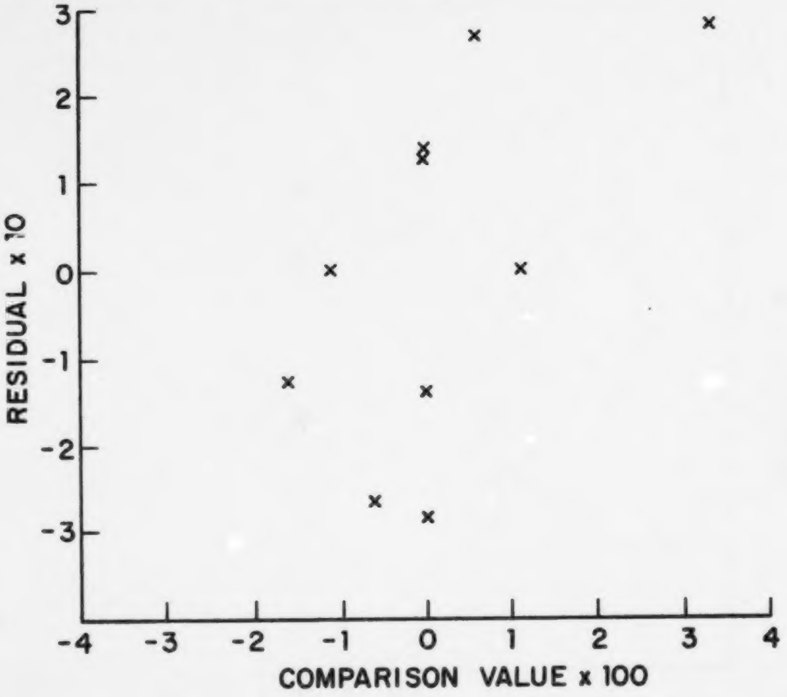


FIGURE A-17. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT, LN (MEDIAN COD, MICROGRAMS/GRAM X .001) CLIMATIC REGION VERSUS LAND USE

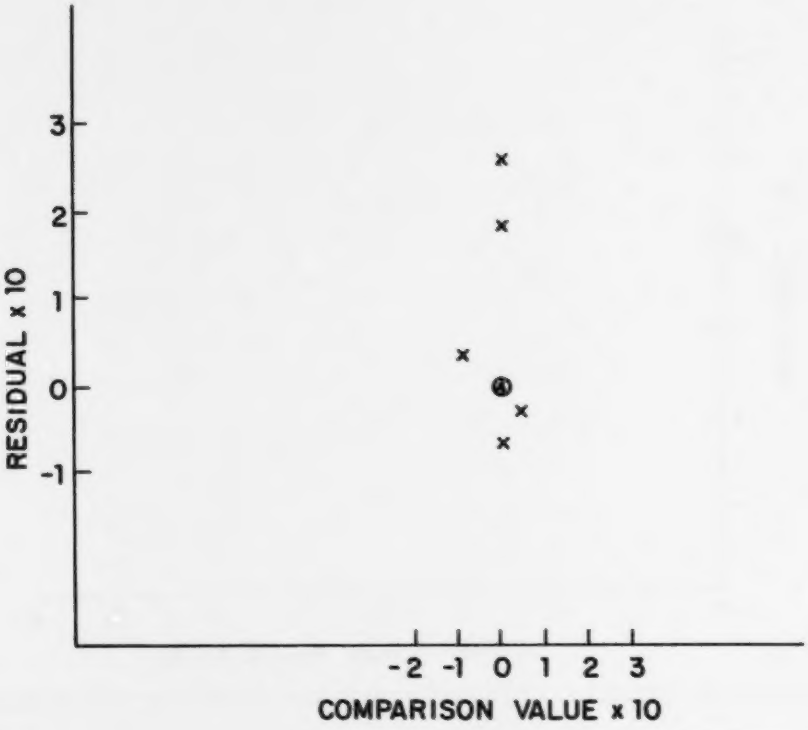


FIGURE A-18. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT,
LN (MEDIAN COD, MICROGRAMS/GRAM X .001)
LAND USE VERSUS AVERAGE DAILY TRAFFIC VOLUME

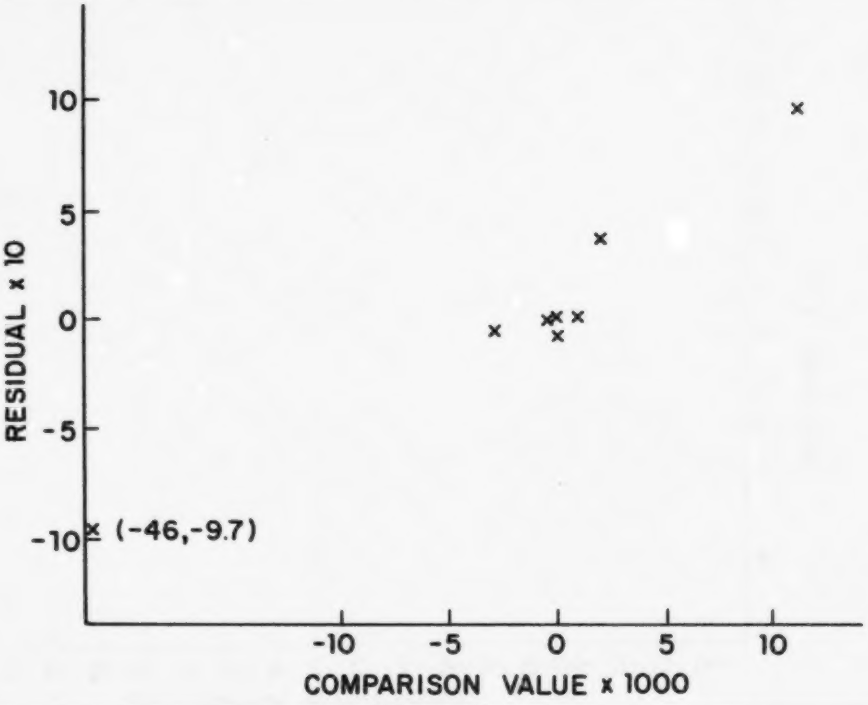


FIGURE A-19. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT,
LN (MEDIAN LEAD, MICROGRAMS/GRAM X .1)
LAND USE VERSUS CLIMATIC REGION

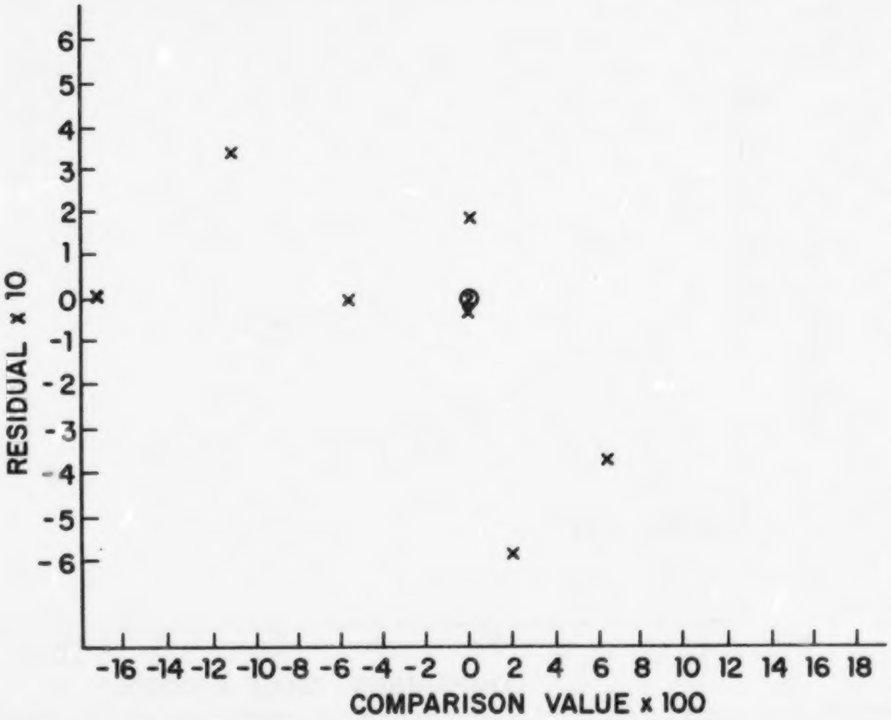
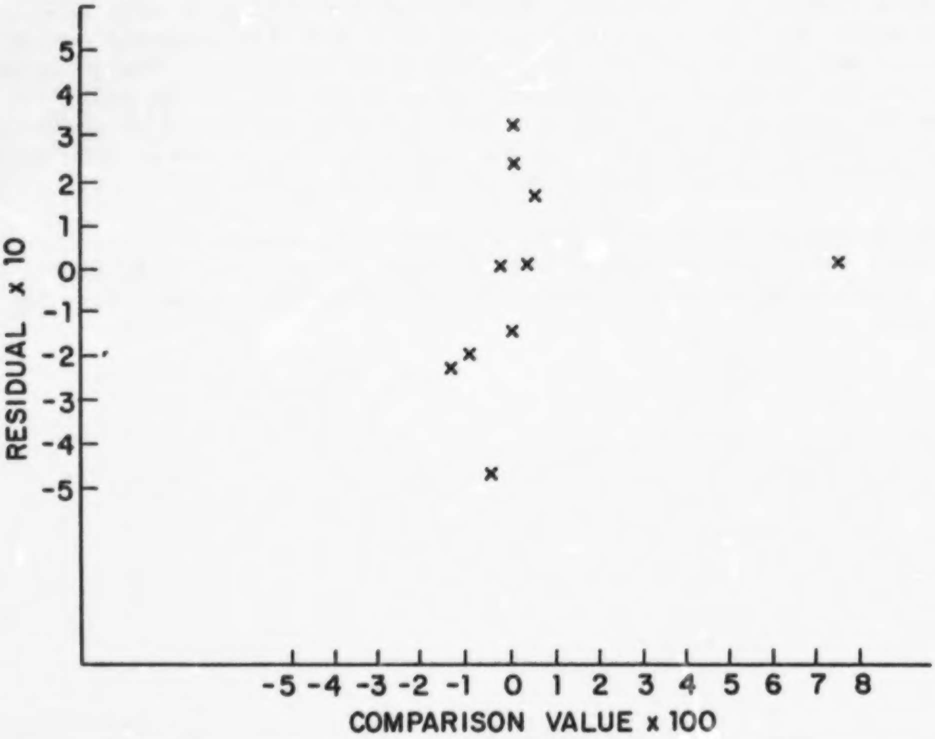


FIGURE A-20. DIAGNOSTIC PLOT RESIDUALS FROM TWO-WAY FIT, LN (MEDIAN LEAD, MICROGRAMS/GRAM X .1) LAND USE VERSUS AVERAGE DAILY TRAFFIC VOLUME



ANALYSIS OF WASHOFF: THE ENVIREX-DOT DATA

Developing the Data-Base

In the analysis of individual storms the relationship of suspended solids to flow was studied by comparing cumulative suspended solids to cumulative flow. A conservative estimate of the quantity accumulating between observations was made by simple linear interpolation in which the observations used to define the intervals were those of the pollutant parameter. However by this method, the flow always had more observations than were used in a regression; some information was not used. For instance, a time interval in a zinc versus flow relationship may be defined by the one-half hour between zinc observations, while a plot of suspended solids versus flow for the same storm permits 15-minute intervals to be used. The zinc versus flow plot will show a linear relationship over the one-half hour interval, but the suspended solids versus flow plot may show a significant non-linear relationship. Though we may suspect that zinc behaves similarly to suspended solids, we are unwilling to assume this *a priori*; consequently, the conservative method of analysis chosen does not reflect this information and may be in error. Where this type of error seemed likely the results were eliminated from this report.

As discussed in the main body of Section 5, several additional explanatory plots were made of washoff constituents versus cumulative flow. The next three graphs display this relationship for iron, TOC, chlorides, total solids, and zinc.

FIGURE A-21. CUMULATIVE Fe AND TOC VERSUS CUMULATIVE FLOW
MILWAUKEE STORM #4

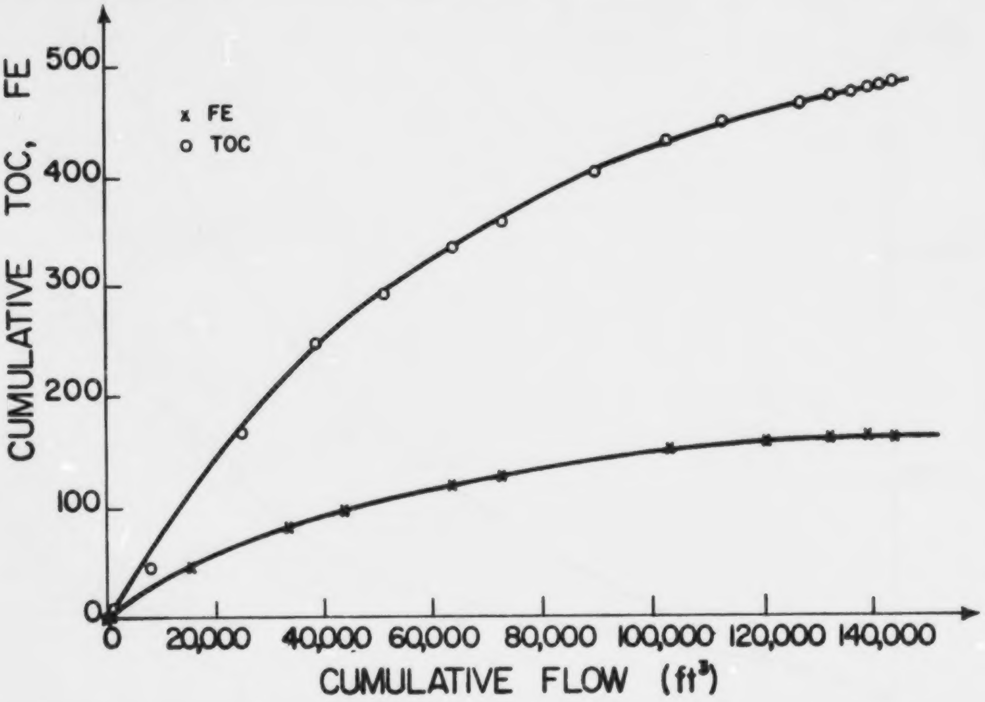


FIGURE A-22. CUMULATIVE CL- TS VERSUS CUMULATIVE FLOW
MILWAUKEE STORM #4

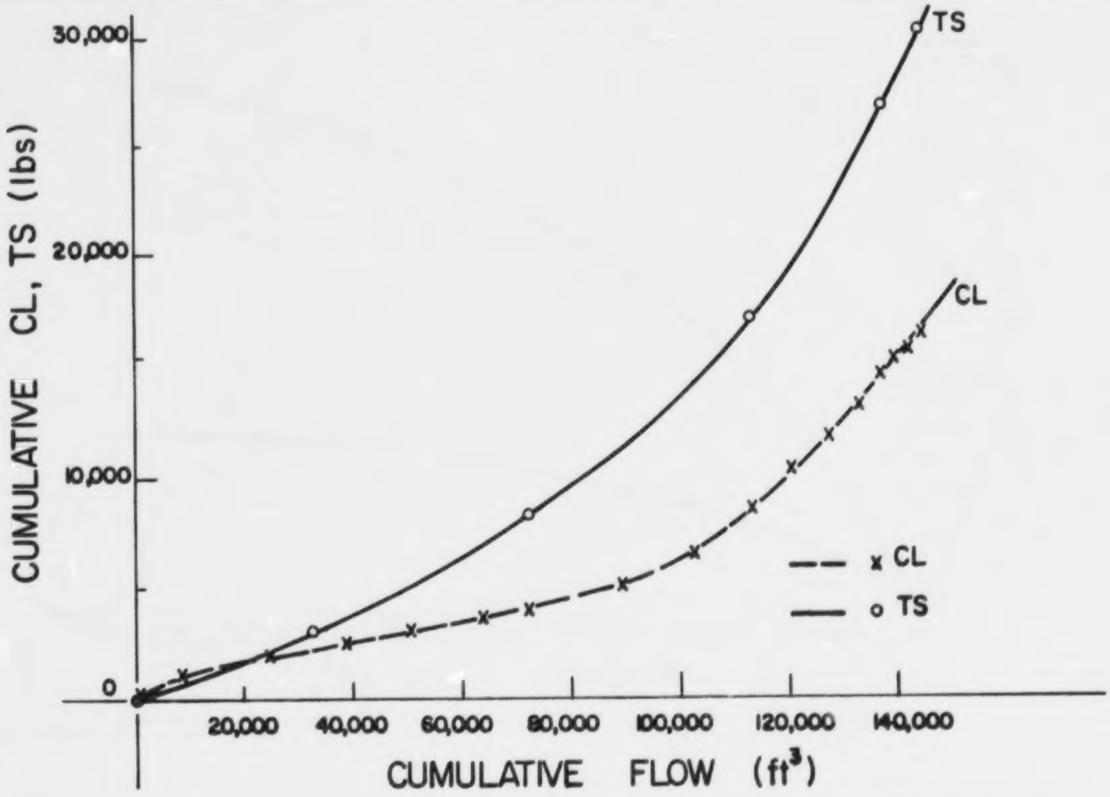
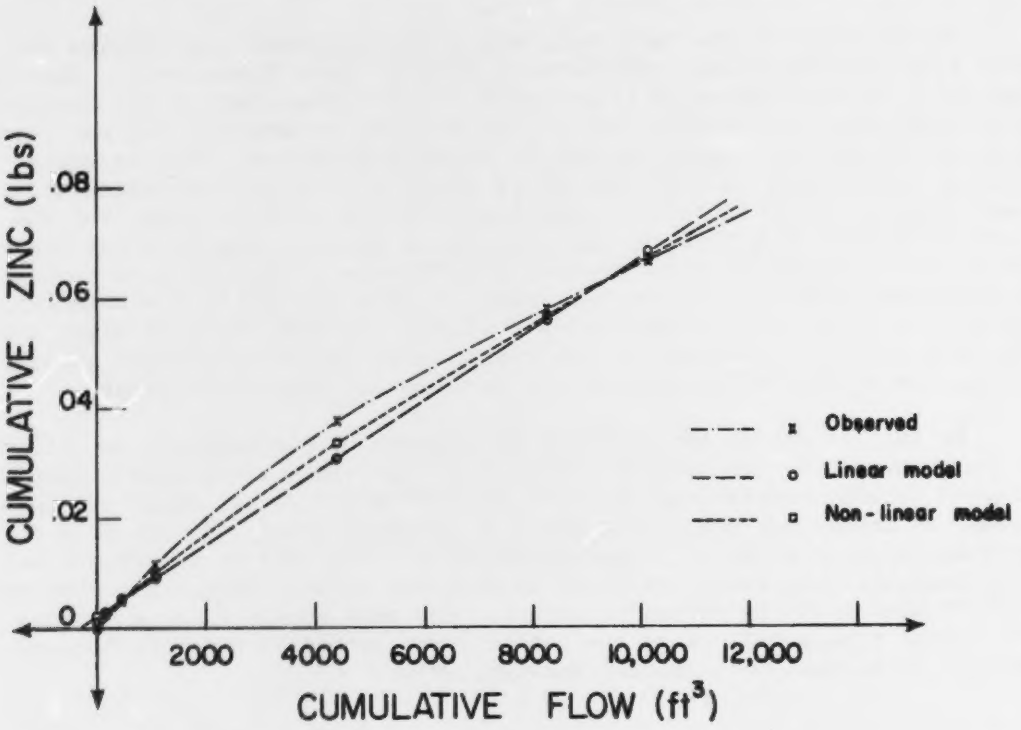


FIGURE A-23. CUMULATIVE ZINC VERSUS CUMULATIVE FLOW
HARRISBURG STORM #7



APPENDIX B

DEVELOPING PRODUCTION FUNCTIONS FOR RUNOFF CONTROL MEASURES

DETAILS OF THE HYDROLOGIC MODEL

As described in the main text, any simulation model must divide the land area considered into hypothetical "blocks" (see Figure B-1). Each block (or cell) is selected so as to be "relatively" independent of its neighbors; this simplifies bookkeeping, but is not strictly necessary. For our interests a block consists of a *pervious* and an *impervious* section, each of which behaves differently in its response to rainfall. In the simulation model this means that it takes different amounts of time for water to flow from the impervious part of a block to our observation point A than from the pervious part. Our observer at point A notes a difference in the lag time -- hence the flow contributions to the hydrograph -- from the pervious and impervious parts of a block. If we keep account of this lag time for each block and for each rainfall interval, we can construct an output hydrograph at point A as the sum of the contributions from pervious and impervious areas.

We further divide the pervious and impervious sub-sections as follows: 1) pervious areas that receive runoff from impervious areas (lawns that are drained into by runoff from rooftops or driveways); 2) all other pervious areas; 3) impervious areas that drain to pervious (roofs, driveways); 4) impervious areas that do not drain to pervious areas; and 5) impervious main road segments (the latter category is designed to deal separately with the section that might be porous pavement). For each sub-section we calculate the runoff from a cell using the runoff curve method of the Soil Conservation Service (U.S. Soil Conservation Service, 1972).

$$\text{runoff } Q = \frac{(P-0.2S)^2}{P+0.8S} \qquad \text{(B-1)}$$

where P = potential maximum runoff (taking into account storage and excess precipitation);

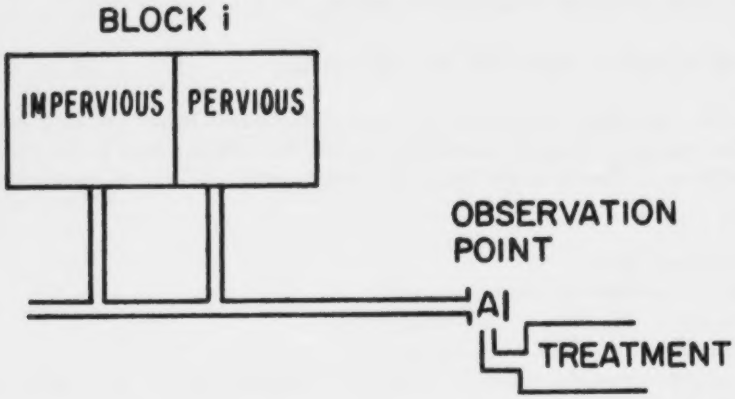
S = retention factor derived from a "curve number" formula;

that is,

$$S = \frac{1000}{CN} - 10 \qquad \text{(B-2)}$$

where CN = curve number based on soil type and antecedent moisture conditions. The curve number ranges from 0 (completely pervious) to 100 (completely impervious).

FIGURE B-1. HYPOTHETICAL DEVELOPMENT BLOCK



The additional information required is the lagtime from the cell to the entry point of the transport/storage system:

$$\text{TRAVEL}\ (i,j) = \frac{l^{0.8}(S+1)^{0.7}}{1900\ Y^{0.5}} \qquad \text{(B-3)}$$

(SCS,1972)

where TRAVEL(i,j) = lag, in hours, from cell i, sub-section j to transport system.

l = length from farthest point in section to transport system

Y = average slope, (percent)

S = as defined above (retention factor).

Flow in cell (i,j) at time K appears in the transport system at time K + TRAVEL(i,j). To obtain the final hydrograph, we simply sum the flows over all times and cells during the storm, lagging for travel time:

$$\text{FLOW(time K)} = \sum_{i=1}^{N} (\text{Pervious area flow }(i,j,K-\text{TRAVEL}(i,j)) + \text{Impervious area flow }(i,j,K-\text{TRAVEL}(i,j))) \qquad \text{(B-4)}$$

The final step entails routing this flow through the transport system using a version of Manning's equation. This simulation model is quite close in form to others using a simple lag-calculation; for example, the ILLUDAS model (1974).

DESIGN OF THE MODEL PROGRAM: DISSOLVED SOLIDS WASHOFF

Solids are first accumulated on the cell sections differentially (according to type). Solids flux is computed by either 1) exponential washoff from impervious areas based on runoff intensity or 2) erosion from pervious areas based on the USLE erosion method (discussed below). Solids from impervious surfaces can wash to pervious ones in the same cell. Solids flow is then lagged using the methods described above.

INCORPORATING CONTROL MEASURES IN THE MODEL

Since all natural features of the site have been incorporated in parameters of the model, runoff controls must be represented through changes in these parameters. The parameters for each cell i and sub-section j are:

area
curve number (CN)
storage of water within the cell
loading rate of solids accumulation
decay rate of solids accumulation
USLE factor-erosion number (See discussion later in this appendix)
slope of cell
hydraulic length of cell

transport hydraulics:

depth of each section of transport system
slope of each section of transport system
length of each section of transport system
bottom width of each section of transport system
Manning's coefficient of each section of transport system
antecedent days since last rain or sweeping
maximum storage and treatment capacity

The control measures and their corresponding parameter changes are given in Table B-1.

In addition, the model has the capability to test a variety of other situations; one that was specifically examined was a change in soil type from relatively pervious to relatively impervious. This was done by changing curve numbers for pervious sub-sections from low to high values.

Three residential development layouts were chosen for simulation:

1. "conventional" development, with quarter-acre lots;
2. "low-density" development, one-acre lots;
3. "cluster-townhouse" development, with four units per townhouse, and clusters of three to five townhouses per cell.

These different development patterns were selected so as to incorporate a broad range of alternatives, from those that develop almost all the area of site (alternative 1, conventional) to those that leave most area untouched

TABLE B-1. MODEL PARAMETERS CHANGED BY CONTROL MEASURES

Control Measure	Parameter Changes
base case (no controls)	no changes
porous pavement	1. area that is road (sub-section 5) becomes part of pervious area (sub-section 1)
	2. curve number = curve number of surrounding soil
	3. storage-unchanged (possibly could add a slight amount)
	4. loading/decay rates: unchanged
	5. slope: unchanged
	6. hydraulic length: unchanged
	7. transport hydraulics: unchanged
swales	all parameters unchanged except roughness and infiltration in transport system. Roughness is increased; infiltration is increased, by a factor of 1.5
roof-gutter disconnection	area = impervious roof area now connected to pervious area
	all other parameters unchanged
on-lot storage	increase storage in pervious subsections of cell to 0.07 inches
vegetative cover	lower curve numbers to about 30-40 for pervious subsections of cell
	lower USLE erosion factor in these subsections, by one-half
street sweeping (not tested)	reduce antecedent days of accumulation

(alternative 2). In addition, alternative 3 (townhouse) lets us test whether one can put the same number of total units onto an area as in conventional developments, but with less impact on the hydrology. All information on standard setbacks, housing unit areas, and general placement of units was taken from the Real Estate Research Corporation (1974).

To summarize, we have the following sets of alternatives to be simulated:

1) three development types: conventional, low-density, cluster
2) two soil regimes: highly pervious, highly impervious

3) six control measures:
   - a. none
   - b. porous pavement
   - c. swales
   - d. roof-gutter disconnection
   - e. on-lot storage
   - f. vegetative cover

There are nine combinations of control measures:
   b,e
   b,c
   d,f
   b,c,d
   b,d,f
   b,e,f
   b,c,d,e
   b,c,d,f
   b,c,d,e,f
total: 15 control alternatives

4) a randomized set of storms with a given distribution over time.

The Development Layouts

For each of the three site layouts seven or eight simulation model cells were formed. Cells were drawn roughly the same size in each layout. The total area covered is about 26.4 acres (10.75 ha). Schematic drawings of the sites are given in Figures B-2 to B-5.

Development Number One: Conventional Design--

Some assumptions made in the conventional design were:

1) House setback 30 feet (7.92 m);
2) Driveway 12 feet wide (3.17 m);
3) House unit is 45 x 35 feet (11.89 x 9.25 m);
4) Main road is 20 feet wide (5.28 m)

Parameter values for each of the cells and their sub-sections are given in Table B-2. Recall that sub-sections are defined as:

1) pervious, draining impervious area (receives runoff from sub-section 4); lawns, open field, etc.;

2) pervious, not draining impervious area;

3) impervious draining to transport system (roof drains, if connected);

4) impervious draining to pervious (driveway, rooftop if not connected to transport system);

5) impervious main road.

Curve numbers are taken from the SCS bulletin 58, pages 2-5. Hydraulic length and slope are from topographic maps. All solids buildup/erosion factors are default values (as used in SWMM); the formulation of the USLE factor is described below.

FIGURE B-2. BOWKER WOODS DEVELOPMENT SITE

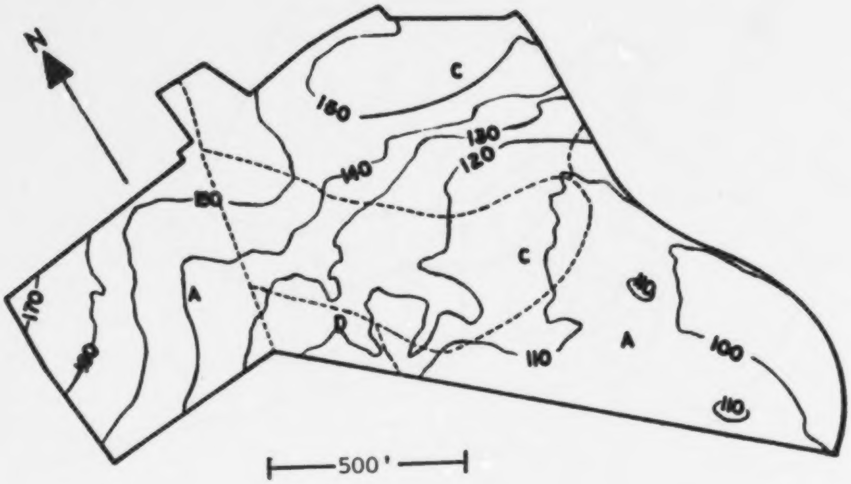

N
C
160
130
120
140
150
170
160
A
D
C
90
110
A
100
110
500'

FIGURE B-3. BOWKER WOODS QUARTER-ACRE DEVELOPMENT ("CONVENTIONAL")

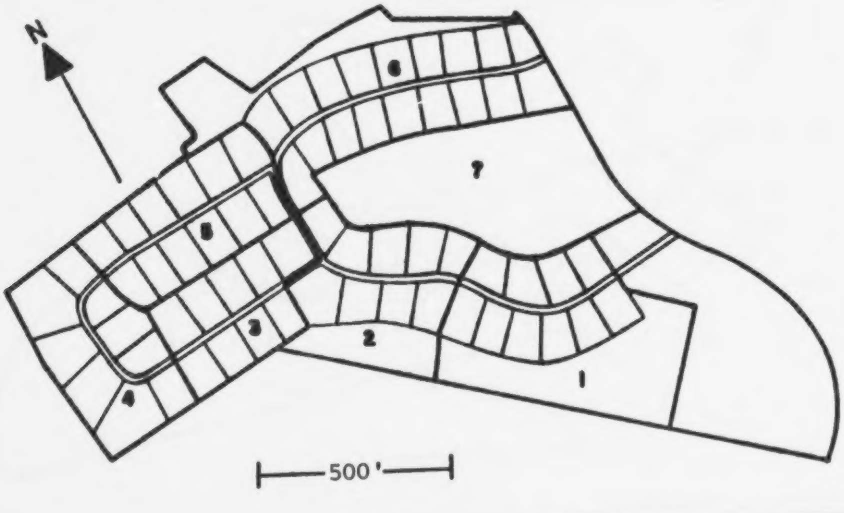

N
6
7
5
3
2
4
1
500'

FIGURE B-4. BOWKER WOODS LOW-DENSITY DEVELOPMENT

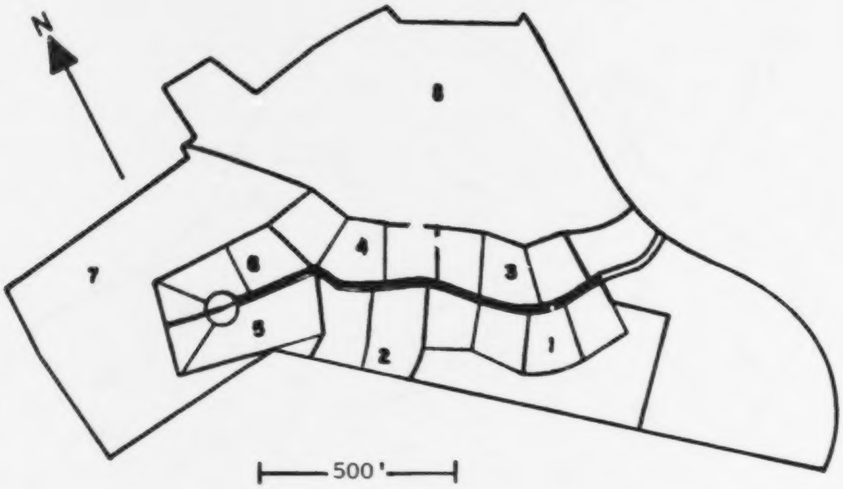

N
8
7
6
4
3
5
2
1
500'

FIGURE B-5. BOWKER WOODS CLUSTER-TOWNHOUSE DEVELOPMENT

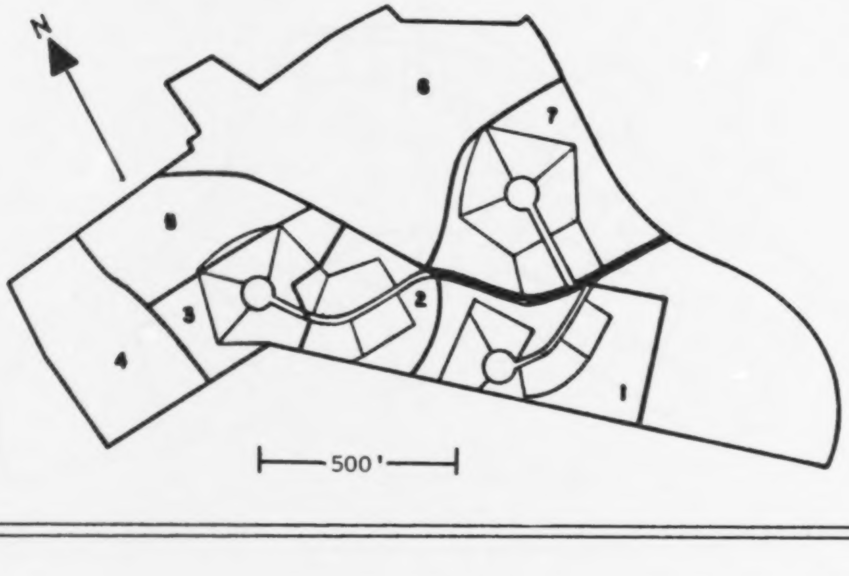

N
6
7
5
3
2
4
1
500'

TABLE B-2. MODEL PARAMETERS FOR CONVENTIONAL DEVELOPMENT

Cell #	Sub-Section#	Area acres	Curve Number	Storage inches	Average Slope,%	hydraulic length,feet	USLE erosion factor	solids deposit* and erosion factors		
1	1	0.2926	49	0	3.5	250	.75	0	.01	0
	2	3.1191	49	0	3.5	400	.75	0	.01	0
soil type=A	3	0.3961	95	0	3.0	70	0	5	.01	0
	4	0.0345	95	0	3.0	60	0	5	.01	0
# Units = 10	5	0.2066	95	0	2.5	75	0	5	.01	0
2	1	0.3696	84	0	4.0	250	.75	0	.01	0
	2	1.0245	84	0	4.0	400	.75	0	.01	0
soil type=D	3	0.3203	95	0	3.0	75	0	5	.01	0
	4	0.0310	95	0	3.0	75	0	5	.01	0
# Units = 9	5	0.1653	95	0	3.0	75	0	5	.01	0
3	1	0.7231	49	0	5.0	300	.75	0	.01	0
	2	1.2237	49	0	5.0	450	.75	0	.01	0
soil type=A	3	0.3564	95	0	4.0	70	0	5	.01	0
	4	0.0310	95	0	3.5	60	0	5	.01	0
# Units = 9	5	0.2066	95	0	3.0	75	0	5	.01	0
4	1	0.4660	49	0	4.0	150	.75	0	.01	0
	2	2.6498	49	0	4.0	200	.75	0	.01	0
soil type=A	3	0.3564	95	0	4.0	70	0	5	.01	0
	4	0.0310	95	0	4.0	60	0	5	.01	0
# Units = 9	5	0.2158	95	0	3.0	75	0	5	.01	0
5	1	0.8597	49	0	4.0	150	.75	0	.01	0
	2	1.2341	49	0	4.0	200	.75	0	.01	0
soil type=A	3	0.4752	95	0	4.0	70	0	5	.01	0
	4	0.0413	95	0	4.0	60	0	5	.01	0
# Units = 12	5	0.2296	95	0	4.0	75	0	5	.01	0
6	1	0.6428	79	0	4.0	200	.75	0	.01	0
	2	4.1246	79	0	4.0	350	.75	0	.01	0
soil type=C	3	0.4994	95	0	4.0	70	0	5	.01	0
	4	0.0655	95	0	4.0	60	0	5	.01	0
# Units = 19	5	0.3673	95	0	3.0	75	0	5	.01	0
7	1	0	79	0	-	-	.75	0	.01	0
	2	5.6918	79	0	4.0	800	.75	0	.01	0
soil type=C	3	0	95	0	-	-	0	5	.01	0
	4	0	95	0	-	-	0	5	.01	0
# Units = 0	5	0	95	0	-	-	0	5	.01	0

*solids deposit and erosion factors are dimensionless

Development Number Two: Low-Density Design--

Table B-3 gives the parameter information for the low-density (1+acre) layout. The number of units placed on the large lots is only 16, roughly corresponding to the density proposed in the actual plan by BSC Engineering (ten units). This means that the percent area that is converted to impervious is much smaller for this type of development than for the conventional development (road and house surface area is smaller).

Additional changes from the conventional layout are:

1) House setback is 60 feet (15.85 m);
2) A housing unit is 50 x 40 feet (13.20 x 10.56 m).

Development Number Three: Cluster Development--

Finally, Table B-4 gives information for the "cluster" development (see also sketch Figure B-5). Each cluster is made up of groups of townhouses -- four units per townhouse. There are 17 clusters for a total of 68 units, so we are constructing the same total number of units as for the conventional layout. Further modifications include the cul-de-sac roads that lead into each cluster; this adds to the surface area taken up by roads. Other modifications are:

1) House setback 30 feet (7.92 m);
2) Each townhouse unit occupies 600 square feet (41.9 m^2, 4 units/townhouse);
3) Cul-de-sac road is 20 feet wide (5.28 m).

TRANSPORT SYSTEM HYDRAULIC PARAMETERS

As described above, it is assumed that the network of cells is connected by a "transport system." This can be either a conventional sewer system (pipes) or open channels. The network drains all cells in a simple upstream-to-downstream order: a cell cannot drain to an adjacent cell, but only to the transport network. A hydrograph is computed by routing and accumulating the flows as they appear in sequence from upstream to downstream along each section of the network that drains an additional particular cell. For example, in the conventional development the upstream-to-downstream order of drainage is Cell Number 4 to transport, then Cells 3, 5, 6, 2, 1 and finally Cell 7. The output is the final output hydrograph after routing through the transport network that drains Cell 7 and all the flow in the network before Cell 7. Notice that in this case the transport system has seven sub-parts.

The parameters required for this routing (which uses Manning's equation) are, for each sub-part:

1) Whether circular pipe or trapezoidal channel flow;
2) depth of channel or pipe (feet);
3) side-slope of channel (not needed if pipe);
4) Manning's coefficient;
5) length of pipe or channel sub-section, feet;
6) diameter of pipe or bottom width of channel, feet;
7) which cell number is drained by this sub-section.

TABLE B-3. MODEL PARAMETERS FOR LOW-DENSITY DEVELOPMENT

Cell #	Sub-Section#	Area acres	Curve number	Storage inches	Average slope, %	hydraulic length,feet	USLE erosion factor	solids deposit and erosion factors		
1	1	0.5670	49	0	3.5	100	.75	0	.01	0
	2	2.2014	49	0	3.5	200	.75	0	.01	0
soil type=A	3	0.1625	95	0	3.0	100	0	5	.01	0
	4	0.0248	95	0	3.0	100	0	5	.01	0
# units = 3	5	0.0746	95	0	2.5	75	0	5	.01	0
2	1	0.3788	84	0	4.0	150	.75	0	.01	0
	2	1.0146	84	0	4.0	250	.75	0	.01	0
soil type=D	3	0.1084	95	0	3.0	100	0	5	.01	0
	4	0.0166	95	0	3.0	100	0	5	.01	0
# units = 2	5	0.0599	95	0	3.0	75	0	5	.01	0
3	1	0.5165	79	0	5.0	200	.75	0	.01	0
	2	0.6538	79	0	5.0	300	.75	0	.01	0
soil type=C	3	0.1645	95	0	4.0	100	0	5	.01	0
	4	0.0248	95	0	3.5	100	0	5	.01	0
# units = 3	5	0.0976	95	0	3.0	75	0	5	.01	0
4	1	0.5165	79	0	4.0	250	.75	0	.01	0
	2	0.7245	79	0	4.0	300	.75	0	.01	0
soil type=C	3	0.1645	95	0	4.0	100	0	5	.01	0
	4	0.0248	95	0	4.0	100	0	5	.01	0
# units = 3	5	0.0804	95	0	3.0	75	0	5	.01	0
5	1	0.4821	49	0	4.0	200	.75	0	.01	0
	2	0.9603	49	0	4.0	300	.75	0	.01	0
soil type=A	3	0.1645	95	0	4.0	100	0	5	.01	0
	4	0.0248	95	0	4.0	100	0	5	.01	0
# units = 3	5	0.0757	95	0	4.0	75	0	5	.01	0
6	1	.5510	49	0	4.0	200	.75	0	.01	0
	2	.7815	49	0	4.0	300	.75	0	.01	0
soil type=A	3	.1166	95	0	4.0	100	0	5	.01	0
	4	.0248	95	0	4.0	100	0	5	.01	0
# units = 2	5	.0757	95	0	3.0	75	0	5	.01	0
7	1	0	49	0	-	-	.75	0	.01	0
	2	6.9903	49	0	4.0	700	.75	0	.01	0
soil type=A	3	0	95	0	-	-	0	5	.01	0
	4	0	95	0	-	-	0	5	.01	0
# units = 0	5	0	95	0	-	-	0	5	.01	0
8	1	0	0	0	-	-	.75	0	.01	0
	2	9.6	79	0	4.0	1000	.75	0	.01	0
soil type=C	3	0	0	0	-	-	0	5	.01	0
	4	0	0	0	-	-	0	5	.01	0
# units = 0	5	0	0	0	-	-	0	5	.01	0

TABLE B-4. MODEL PARAMETERS FOR TOWNHOUSE DEVELOPMENT

Cell #	Sub-Section	Area Acres	Curve Number	Storage inches	Average slope,%	hydraulic length,feet	USLE erosion factor	solids deposit and erosion factors		
1	1	0.0899	49	0	3.5	250	.75	0	.01	0
	2	0.5957	49	0	3.5	350	.75	0	.01	0
Soil type=A	3	0.4089	95	0	3.0	150	0	5	.01	0
	4	0.1338	95	0	3.0	100	0	5	.01	0
#Clusters=4	5	0.1116	95	0	2.5	100	0	5	.01	0
2	1	0.6313	84	0	4.0	250	.75	0	.01	0
	2	0.8616	84	0	4.0	350	.75	0	.01	0
soil type=D	3	0.2134	95	0	3.0	150	0	5	.01	0
	4	0.0206	95	0	3.0	100	0	5	.01	0
#Clusters=3	5	0.1837	95	0	3.0	75	0	5	.01	0
3	1	0.6211	49	0	5.0	150	.75	0	.01	0
	2	1.4757	49	0	5.0	250	.75	0	.01	0
soil type=D	3	0.2204	95	0	4.0	100	0	5	.01	0
	4	0.1141	95	0	3.5	100	0	5	.01	0
#Clusters=4	5	0.1096	95	0	3.0	75	0	5	.01	0
4	1	0	49	0	-	-	.75	0	.01	0
	2	3.719	49	0	4.0	450	.75	0	.01	0
soil type=D	3	0	95	0	-	-	0	5	.01	0
	4	0	95	0	-	-	0	5	.01	0
#Clusters=0	5	0	95	0	-	-	0	5	.01	0
5	1	0	49	0	-	-	.75	0	.01	0
	2	2.5069	49	0	4.5	700	.75	0	.01	0
soil type=D	3	0	95	0	-	-	0	5	.01	0
	4	0	95	0	-	-	0	5	.01	0
#Clusters=0	5	0	95	0	-	-	0	5	.01	0
6	1	0	79	0	-	-	.75	0	.01	0
	2	7.4875	79	0	4.5	550	.75	0	.01	0
soil type=C	3	0	95	0	-	-	0	5	.01	0
	4	0	95	0	-	-	0	5	.01	0
#Clusters=0	5	0	95	0	-	-	0	5	.01	0
7	1	0.5510	79	0	4.5	250	.75	0	.01	0
	2	3.1035	79	0	4.5	350	.75	0	.01	0
soil type=C	3	0.3489	95	0	4.0	150	0	5	.01	0
	4	0.0183	95	0	3.5	100	0	5	.01	0
#Clusters=6	5	0.1377	95	0	3.0	100	0	5	.01	0

Table B-5 gives the values for these parameters used in the simulations. Figure B-6 gives sample output from the program. A complete listing of the program is supplied in Appendix C.

TABLE B-5. TRANSPORT SYSTEM PARAMETERS (CONVENTIONAL DEVELOPMENT)

Depth of Channel or Pipe	Side Slope	Manning's Coefficient	Length	Diameter (bottom width)	Channel Number
.75	-	.015	200	.75	4
.75	-	.015	300	.75	3
.75	-	.015	350	.75	5
.75	-	.015	350	.75	6
.75	-	.015	200	.75	2
.75	-	.015	250	.75	1
1	3	.025	350	2	7

LIMITATIONS OF THE MODEL

Like any computer model, the control measure simulation model must bear the inherent weaknesses of its parts. These fall into the usual categories: data uncertainties and the substitution of simple models for physical processes instead of the "correct" ones.

Hydrology

- simple classification into pervious/impervious areas.
- inadequate physical modeling in the use of Manning's equation for overland or sewer flow instead of kinematic wave equation.
- no provision for complex detention of water besides initial abstraction in SCS method.
- use of SCS lagtime equation.
- use of SCS methods applied to extremely small time increments, for which little verification has been made.

Solids

- exponential washoff model "K" factor uncertain.
- no disaggregation into particle size classes.
- use of USLE-type erosion model, not generally used for time increments within a storm.

Control Measures

- need to more adequately model effects of porous pavement, vegetative cover, etc; what other parameters need be included to do this?

As a result, the model can be used only to demonstrate comparative control measure effectiveness. It cannot be used to accurately model a real watershed, especially without calibration. On the other hand, the deficiencies described above could quite easily be remedied; the existing model is already comparable to a model like ILLUDAS and gives quite reasonable results.

FIGURE B-6. SAMPLE OUTPUT FROM COMPUTER PROGRAM

```
CONVENTIONAL QUARTER-ACRE; CONTROL OPTIONS SELECTED=SWALES
         FLOW & SOLIDS-->                                                                 <-- CUMULATIVE RAIN
                                                                                                       3.5       1.7      0.0
    +....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+
0.0 +S                                                                                                                     P|
    |S                                     ** MONTE CARLO SIMULATION **                                                    P|
    |S                                                                                                                     P|
    |S                                                                                                                     P|
    |S                                                                                                                    P |
0.12+S                                                                                                                    P |
    |S                                                                                                                  P   |
    |S                                                             NOTE:                                             P      |
    |S*                                                                                                            P        |
    |*S**********                                                  FLOW INCREMENTS=             0.005 cfs         P         |
0.27+*S*********************                                       FLOW MAX=                    0.500 cfs         P         |
    |*S*************************                                                                                  P         |
    |*S*********************                                       SOLIDS INCREMENTS=           1.200 lbs         P         |
    |*S****************                                            SOLIDS MAX=                120.000 lbs         P         |
    |S*************                                                RAIN(CUM.)=                  0.175 inches      P         |
0.42+S**********                                                                                                  P         |
    |S*******                                                      RAIN (MAX CUM.)=             3.500 inches      P         |
    |S*****                                                                                                       P         |
    |S***                                                                                                         P         |
    |S**                                                                                                          P         |
0.57+S*                                                                                                           P         |
    |S*                                                                                                           P         |
    |S                                                                                                            P         |
    |S                                                                                                            P         |
    |************S***                                                                                             P         |
0.72+S***********                                                                                                 P         |
    |***************S                                                                                             P         |
    |S**********                                                                                                  P         |
    |********   S                                                                                                 P         |
    |S*****                                                                                                       P         |
0.87+****   S                                                                                                     P         |
    |S**                                                                                                          P         |
    |**   S                                                                                                       P         |
    |S*                                                                                                           P         |
    |*  S                                                                                                         P         |
1.02+S                                                                                                            P         |
    |* S                                                                                                          P         |
    +....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+....+
   0.0       0.05      0.1       0.15      0.2       0.25      0.3       0.35      0.4       0.45      0.5
   0.0      12.0      24.0      36.0      48.0      60.0      72.0      84.0      96.0     106.0     120.0
         FLOW & SOLIDS-->                                                                 <-- CUMULATIVE RAIN

PRECIPITATION=  0.0174       0.0174       0.0694       0.1041       0.1388       0.5726       1.1453       1.4403
```

FIGURE B-6. (CONTINUED)

```
STORM:    2 ANTECEDENT DRY PD:  200 PRECIP DURATION:    23 EVENT DURATION:    36 ANTE MOISTURE COND:    2 CASE:     1

I      P       CP      QI      SQI     FSI     SSI     CI      QD      SQD     FSD     SSD     CD      FSR     SSR
1   0.017   0.017   0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
2   0.052   0.069   0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
3   0.104   0.174   0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
4   0.035   0.208   0.000   0.000   0.002   0.002   0.275   0.0     0.0     0.0     0.0     0.0     0.0     0.0
5   0.069   0.278   0.000   0.001   0.028   0.030   0.259   0.0     0.0     0.0     0.0     0.0     0.0     0.0
6   0.416   0.694   0.003   0.004   0.189   0.219   0.242   0.0     0.0     0.0     0.0     0.0     0.0     0.0
7   0.469   1.163   0.005   0.008   0.144   0.363   0.140   0.0     0.0     0.0     0.0     0.0     0.0     0.0
8   0.312   1.475   0.009   0.017   0.445   0.809   0.227   0.0     0.0     0.0     0.0     0.0     0.0     0.0
9   0.104   1.579   0.058   0.075   2.323   3.131   0.177   0.0     0.0     0.0     0.0     0.0     0.0     0.0
10  0.035   1.614   0.115   0.190   1.959   5.091   0.075   0.0     0.0     0.0     0.0     0.0     0.0     0.0
11  0.035   1.649   0.135   0.325   2.230   7.320   0.073   0.0     0.0     0.0     0.0     0.0     0.0     0.0
12  0.035   1.683   0.113   0.438   1.521   8.841   0.059   0.0     0.0     0.0     0.0     0.0     0.0     0.0
13  0.0     1.683   0.086   0.525   1.617  10.458   0.083   0.0     0.0     0.0     0.0     0.0     0.0     0.0
14  0.0     1.683   0.067   0.592   1.113  11.572   0.073   0.0     0.0     0.0     0.0     0.0     0.0     0.0
15  0.0     1.683   0.053   0.645   1.179  12.751   0.097   0.0     0.0     0.0     0.0     0.0     0.0     0.0
16  0.0     1.683   0.038   0.683   0.788  13.538   0.092   0.0     0.0     0.0     0.0     0.0     0.0     0.0
17  0.0     1.683   0.027   0.710   0.834  14.372   0.137   0.0     0.0     0.0     0.0     0.0     0.0     0.0
18  0.0     1.683   0.019   0.729   0.557  14.929   0.130   0.0     0.0     0.0     0.0     0.0     0.0     0.0
19  0.0     1.683   0.013   0.742   0.590  15.520   0.194   0.0     0.0     0.0     0.0     0.0     0.0     0.0
20  0.0     1.683   0.009   0.751   0.394  15.914   0.183   0.0     0.0     0.0     0.0     0.0     0.0     0.0
21  0.035   1.718   0.007   0.758   0.418  16.331   0.274   0.0     0.0     0.0     0.0     0.0     0.0     0.0
22  0.0     1.718   0.005   0.763   0.279  16.610   0.259   0.0     0.0     0.0     0.0     0.0     0.0     0.0
23  0.017   1.735   0.003   0.766   0.295  16.906   0.368   0.0     0.0     0.0     0.0     0.0     0.0     0.0
24  0.0     1.735   0.080   0.846  15.456  32.361   0.851   0.0     0.0     0.0     0.0     0.0     0.0     0.0
25  0.0     1.735   0.057   0.903   0.209  32.570   0.016   0.0     0.0     0.0     0.0     0.0     0.0     0.0
26  0.0     1.735   0.073   0.976  19.182  51.753   1.158   0.0     0.0     0.0     0.0     0.0     0.0     0.0
27  0.0     1.735   0.052   1.028   0.148  51.901   0.013   0.028   0.028   0.080   0.080   0.013   0.0     0.0
28  0.0     1.735   0.037   1.064  13.571  65.472   1.637   0.037   0.064  13.571  13.651   1.637   0.0     0.0
29  0.0     1.735   0.026   1.090   0.105  65.577   0.018   0.026   0.090   0.105  13.756   0.018   0.0     0.0
30  0.0     1.735   0.018   1.108   9.602  75.178   2.314   0.018   0.108   9.602  23.357   2.314   0.0     0.0
31  0.0     1.735   0.013   1.121   0.074  75.252   0.025   0.013   0.121   0.074  23.431   0.025   0.0     0.0
32  0.0     1.735   0.009   1.131   6.793  82.046   3.271   0.009   0.131   6.793  30.224   3.271   0.0     0.0
33  0.0     1.735   0.006   1.137   0.052  82.098   0.036   0.006   0.137   0.052  30.277   0.036   0.0     0.0
34  0.0     1.735   0.005   1.142   4.806  86.904   4.623   0.005   0.142   4.806  35.083   4.623   0.0     0.0
35  0.0     1.735   0.003   1.145   0.037  86.941   0.050   0.003   0.145   0.037  35.120   0.050   0.0     0.0
36  0.0     1.735   0.002   1.147   3.400  90.341   6.535   0.002   0.147   3.400  38.520   6.535   0.0     0.0

EVENT TOTALS INCLUDING STORED VOLUME AND SOLIDS
DISCHARGE VOLUME =          1.15
DISCHARGE SOLIDS =         48.88
REMOVED SOLIDS =        41.46
STORAGE/TREATMENT EFFICIENCY =        0.459
```

Define variables:

P=precipitation
CP=cumulative precipitation
QI=incremental flow
SQI=cumulative flow
FSI=incremental solids flow
SSI=cumulative solids flow
CI=concentration
QD=flow stored
SQD=cumulative flow stored
FSD=solids stored
SSD=cumulative solids stored
CD=concentration stored
FSR=flow not stored
SSR=solids not stored

THE SIMULATION MODEL: A FLOWCHART

The computer model is a straightforward encoding of the simple rain-washoff-transport components.

The first routine, Main, initializes various control options that affect the simulation generally: the number of subdivision layouts; the number of control option bundles to be simulated; the time increment used; and whether Monte Carlo sampling for storms is to be employed. Main's other function is to call a series of subroutines that do the actual work of the simulation. They are as follows:

1) SETCEL -- reads in parameters that describe each watershed "cell" (area, SCS runoff curve number, storage on-site, pollutant buildup and washoff rates, slope, and hydraulic "length"); computes time-lag for runoff from that cell to the transport system.
2) SAMPLE -- is called next if Monte Carlo sampling has been selected. Given a mean storm volume supplied by the user, SAMPLE makes preliminary calculations to distribute that volume over an empirically supplied storm distribution.
3) SETSTM -- uses one of two methods to develop a cumulative hyetograph (synthetic storm).
    a) reads in actual storm data from cards
    b) if Monte Carlo method is used, allocates the volume randomly according to the supplied rainfall distribution.
4) CONTRL -- reads what control measures have been selected; determines effects on the model parameters.
5) STORM -- using the Soil Conservation Service Method, determines antecedent moisture conditions, updated runoff curve values for each cell, and updated pollutant loadings given the washoff/buildup equation.
6) CELL -- calculates the runoff from all cells and solids washoff from impervious cells, using the SCS Method.
7) TRANSP -- transports the resulting flow from all cells via Manning's equation to a treatment/storage point.
8) ROUTE -- is called by TRANSP and does the actual work of calculating time delays in the transport system. Pipe or channel flow can be selected for a series of channels.
9) TREAT -- routes the flow after transport through a storage/treatment system and determines whether its capacity is exceeded.
10) RESULT -- prints a table of flow, solids flux, and washoff over time.
11) GRAPH -- plots a cumulative hyetograph, a hydrograph, and a pollutograph (solids flux).
12) UNCNTL -- undoes effects of control measures, to prepare for next simulation.

Routines 3-12 are executed first for each control measure bundle selected and then for a series of random draws from the user-supplied storm distribution. Finally, if a series of subdivision layouts is chosen, routines 1-12 are run through in sequence. The result is a simulated "experimental design" of a number of control measures and layouts observed under randomly varying storm conditions.

Description of Routines

MAIN

```
    1.0  read number of layout cases to be simulated;
    2.0  read unit conversion factors;
    3.0  loop over number of cases;
         3.1  read number of cells, storms, control groups, whether sampling
              to be done, time increment (variables NC, NSTO, NCO, SAMPL,
              TINC);
         3.2  write out the values of these variables;
         3.3  read model parameters for antecedent moisture factors, runoff
              decay constant, initial abstraction;
         3.4  read storage/treatment parameters (maximum storage, treatment
              levels);
         3.5  write out 3.3 and 3.4 values;
         3.6  read title for this case;
         3.7  call SETCEL;
         3.8  if SAMPL is true, call SAMPLE (VOLUME);
         3.9  for each control group;
              3.9.1  Call CONTRL;
              3.9.2  For each STORM;
                     3.9.2.1  call SETSTM (SEED, VOLUME);
                     3.9.2.2  call STORM;
                     3.9.2.3  call CELL;
                     3.9.2.4  call TRANSP;
                     3.9.2.5  call TREAT;
                     3.9.2.6  call RESULT;
                     3.9.2.7  call GRAPH;
              3.9.3  end loop over storms;
    4.0  end loop over control groups;
    5.0  end loop over cases;
    6.0  end.
```

SAMPLE

```
1.0  read number of antecedent days, (NTA); number of times periods in storm (NTD), storm total volume;
2.0  get random number from uniform distribution between 0 and 1;
3.0  adjust total volume based on random number and set volume increment for storm;
4.0  read distribution for synthetic storms;
5.0  return to MAIN.
```

SETSTM (SEED, VOLUME)

```
1.0  write header message;
2.0  get 100 random numbers from uniform distribution using random start SEED;
3.0  put volume increments into "bins", distribution (1), ..., distribution (NTD) based on the random numbers, giving rainfall distribution;
4.0  find cumulative precipitation based on this rainfall distribution; write cumulative precipitation;
5.0  return to MAIN.
```

ROUTE (PIPE, DB, SIDE, DEPTH, MANNING, SLOPE, LENGTH, Q, VEL, TI)

```
1.0  find trapezoidal or pipe flow hydraulic radius through this channel;
     1.1  set DEPTH=full depth;
     1.2  calculate flow using Manning equation based on this depth;
     1.3  if equal to flow, return as radius;
     1.4  if not, decrement and iterate to 1.2.
2.0  if no proper depth found, triple depth and try again;
3.0  using final hydraulic radius, compute cross-section using flow and Manning equation;
4.0  compute velocity as flow/area;
5.0  compute TI=travel time=length/velocity;
6.0  return to TRANSP.
```

TRANSP

```
1.0  zero out flow, solids arrays;
2.0  loop over time intervals (1 to NTD); loop over each cell (1 to NC); loop over each sub-section;
     2.1  get time lag to transport for this sub-section;
     2.2  add flow lagged by this amount into flow from this cell;
```

```
3.0 loop over cells J=1 to NC;
    3.1 get cell number that is drained by this part of transport
        system (starting upstream), from array CONECT, NODE=CONECT (J);
    3.2 get channel characteristics for this part of channel:
        DB1   = DB(NODE);
        Z     = SIDE(NODE);
        S1    = SLOPE(NODE);
        Y     = DEPTH(NODE);
        AL    = LENGTH(NODE);
        NØ    = MANNING'S(NODE);
        PIPE2 = PIPE(NODE);
    3.3 adjust NØ if swales;
    3.4 find area of channel or pipe;
    3.5 find hydraulic radius; compute maximum discharge;
    3.6 loop through flow for this cell and see if 0 or exceeds
        maximum; set to maximum if latter;
    3.7 find average flow Q1;
    3.8 route using this flow:
        call ROUTE (PIPE2,DB1,2,Y,NØ,S1,AL,Q1,VEL,TI);
    3.9 shift flow, and solids according to lag TI;
4.0 save this flow and move to next downstream node;
5.0 save final flows, solids;
6.0 return to MAIN.
```

GRAPH

```
1.0 set maximum flow, rain, solids;
2.0 find graph increments;
3.0 write title, top heading;
4.0 loop over time intervals (1 to NLST);
    4.1 blank out line;
    4.2 find graph positions for flow, solids, rain;
    4.3 write out time, line;
5.0 write trailer;
6.0 return to MAIN.
```

CONTRL

```
1.0 read control option card;
2.0 save old parameter values in arrays SAVE, SAVE2,SAVE3, AND SAVE4;
3.0 look for valid option numbers;
```

```
        3.1  if valid, branch to proper control option and adjust
             parameters;
             3.1.1  porous pavement;
             3.1.2  vegetative cover;
             3.1.3  roof-drains disconnection;
             3.1.4  on-lot storage;
             3.1.5  swales;
             3.1.6  soil type impervious;
             3.1.7  unused;
        3.2  all others, write invalid option message, keep looking;
   4.0  if 0 option, print 'end of controls' message and return to MAIN.
```

UNCNTL

```
   1.0  restore old values of parameters from arrays SAVE, SAVE2, SAVE3,
        and SAVE4;
        1.1  loop through all cells (1 to NC);
        1.2  loop through all sub-sections (1 to 5);
   2.0  return to MAIN.
```

RESULT

```
   1.0  write heading;
   2.0  for each time period in STORM (1 to NLST);
   3.0  write out results time, rain, cumulative rain, flow, cumulative
        flow, solids flux, cumulative solids, concentration, flow stored,
        cumulative flow stored, solids stored, cumulative solids stored,
        storage concentrations;
   4.0  compute and write out total volume, solids, removed solids,
        storage/treatment ratio;
   5.0  return to MAIN program.
```

SETCEL

```
   1.0  for each cell,
        1.1  for each of 5 sub-sections
             1.1.1  read cell#, sub-section#, area, curve number, storage,
                    solid buildup rate, decay rates, USLE factor, slope,
                    length;
             1.1.2  calculate lag-time to transport;
             1.1.3  convert to number of time-increments;
             1.1.4  calculate maximum load possible in exponential solids
                    accumulation equation = buildup/decay;
        1.1.5 write out cell parameters;
        1.1.6 find maximum time lag; accumulate total area;
    1.2 read number of channels in transport system;
        1.2.1 for each channel
            1.2.1.1 read whether a pipe, depth, slope, side length (channel only), Manning's coefficient, length, bottom-width or diameter, cell number this channel connects
2.0 return to MAIN program.
```

STORM

```
1.0 if not using Monte Carlo method, read antecedent rain conditions, number of time increments in storm, cumulative precipitation;
2.0 compute antecedent moisture condition factors: multiplier for antecedent moisture conditions 1, 2, or 3 (U.S. Soil Conservation), 1 = 2.4 (dry soils); 2 = 1.0 (average antecedent condition), 3 = 0.420 (saturated);
3.0 compute retention factor S = 1000/curve number - 10;
4.0 adjust retention factor based on antecedent moisture: S=S*antecedent moisture factor (more saturated = lower S value).
5.0 find change in solids accumulation, using formula for load,
    $w = \frac{k_2}{k_1} (1-e^{-Krt})$;
6.0 return to MAIN program.
```

CELL

```
1.0 for each cell;
    1.1 for each time increment (1 to NTD) compute excess precipitation: test = cumulative precipitation - storage-runoff curve retention factor;
    1.2 compute runoff, $Q = \frac{test^2}{test+S}$, where S = retention factor (see routine STORM); add runoff from impervious areas to pervious areas;
    1.3 find increment in flow this time period by subtracting flow of last period;
    1.4 find solids washoff, from impervious areas $w(1-e^{-kt})$;
    1.5 find erosion, FS = erosion = $USLE*(Q^2/TINC)^{0.56}$;
    1.6 find this time period precipitation;
    1.7 add solids flux from impervious to pervious areas;
    2.0  end loop around time increment, and cells;
    3.0  return to MAIN.
```

TREAT

```
    1.0  set initial conditions on storage;
    2.0  ROUTE flow into storage;
         2.1  accumulate volume;
         2.2  check if storage filled (VSMAX);
         2.3  accumulate volume in storage, VS;
    3.0  ROUTE through treatment;
         3.1  check for treatment capacity, QTMAX;
         3.2  check for solids removed;
         3.3  compute ratios, solids treated/total solids;
    4.0  return to MAIN.
```

Erosion Estimate

The method used to estimate erosion in the simulation model is based upon a modification of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1972), introduced by Williams (1972).

In place of the rainfall erosivity factor in the USLE, Williams used peak runoff rate and total storm runoff volume as measures of the erosivity of a given storm. Empirical calibration based upon data from 18 Texas watersheds gave the following result.

$$W = 95 \, (Qq_p)^{.56} KCPL_s \tag{B-5}$$

where W = sediment yield per event (tons);
Q = volume of runoff (acre-ft);
q_p = peak runoff rate (cfs);
K = soil erodibility factor in USLE;
C = cover factors in USLE;
P = practice factor in USLE;
L_s = length/slope factor in USLE.

Values of the four USLE factors are tabulated in Wischmeier and Smith (1972) for specific watershed conditions.

This relationship is applied to each time increment in the simulation to estimate erosion rates from pervious areas. With appropriate unit transformations, equation (B-5) is equivalent to

$$W' = 4.75 \times 10^4 \left[\left(\frac{Q_i^{\ 2}}{\Delta t} \right) \right]^{.56} KCPL_s \qquad \text{(B-6)}$$

where W' = sediment yield (lbs/time increment);

Q_i = runoff volume (acre-inch/time increment);

Δt = time increment size (hours).

The following USLE factors are assumed as being typical of a grassed area with a two percent slope, a slope length of 200 feet, and a soil of intermediate erodibility:

$K = .25$
$C = .01$
$P = 1$
$L_s = .3$

$KCPL_s$ is the term "USLE" in the model.

The above scheme is expected to give only order of magnitude estimates of erosion rates for stable watershed conditions. Use of Williams' formulation on an incremental basis is actually not appropriate, since it has been derived on a total storm event basis. Simulations indicate, however, that erosion rates are generally insignificant compared with solids accumulation and washoff from impervious areas. More detailed simulations of the erosion process that consider the generation and transport of sediment particles in overland flow are not justified, provided that pervious areas are well-vegetated. The above procedure may not be adequate for predicting erosion losses during construction periods in which bare soil is exposed. Under such conditions it may be desirable to resort to a more complex simulation approach (Donigian and Crawford, 1976) or to use the Williams' formulation on a total storm event basis.

APPENDIX C

LISTING OF COMPUTER PROGRAM

```
FORTRAN IV G1  RELEASE 2.0              MAIN                 DATE = 78198          10/01/10

C MAIN PROGRAM - EDISON SIMULATION
      COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
     5F41(10),JCASE,NTA
      COMMON /CHAN/ DB(10),SLOPE(10),LENGTH(10),DEPTH(10),SIDE(10),
     1                  AN(10),DISTRB(100),CONECT(10),PIPE(10)
      COMMON /SWTCH/ OPTION(10),SAMPL,SWALES
      COMMON /TITL/ TITLE(20)
      REAL*8 SEED
      REAL KTS,KTT
      INTEGER*2 OPTION,CONECT
      LOGICAL*1 PIPE,SWALES,SAMPL
      NIN = 5
      NOUT = 6
      NSIN = 5
      NCIN = 5
      READ(NIN,1010) NCASE
 1010 FORMAT(4I5,4X,L1,F10.0)
      READ(NIN,102)   (UNIT(I),I=1,6)
 102  FORMAT(10F6.0)
      DO 100 ICASE = 1,NCASE
      READ(NIN,1010) JCASE,NC,NSTO,NCO,SAMPL,TINC
C
C*       NCO= NUMBER OF CONTROL OPTION COMBOS
C
      WRITE(NOUT,204) JCASE,NC,NSTO,NCO,TINC
 204  FORMAT('1',' CASE = ',I3, ' NO. CELLS = ',I3,' NO. STORMS = ',I3,
     1    ' NO. CONTROL GROUPS= ',I3/
     2' TIME INCREMENT = ',F6.3,' HOURS'/)
      READ(NIN,103) P1,P2,(FAC(J),J=1,3),PLAST,XKW,(FIA(K),K=1,5)
      READ(NIN,103) VSMAX,QSMAX,KTS,VTMAX,QTMAX,KTT
      WRITE(NOUT,201) P1,P2,(FAC(J),J=1,3),PLAST,XKW,(FIA(K),K=1,4)
 201  FORMAT(//  ' MODEL PARAMETERS '/(5X,10F10.3))
      WRITE(NOUT,202) VSMAX,QSMAX,KTS,VTMAX,QTMAX,KTT
 202  FORMAT(//' STORAGE/TREATMENT PARAMETERS'/(5X,10F10.3))
      WRITE(6,203) (UNIT(I),I=1,6)
 203  FORMAT(//' UNIT PARAMETERS'/(5X,10F10.3))
      QSMAX = QSMAX*TINC
      QTMAX = QTMAX*TINC
 103  FORMAT(5X,12F6.0)
      READ(5,1090) TITLE
 1090 FORMAT(20A4)
      CALL SETCEL
      IF(SAMPL) CALL SAMPLE(VOLUME)
C*          RANDOM SEED FOR THIS SET OF STORMS
      SEED=0.3711248
      DO 210 J=1,NCO
      CALL CONTRL
      DO 200 IS = 1,NSTO
      IF(SAMPL) CALL SETSTM(SEED,VOLUME)
 0041                   CALL STORM
 0042                   CALL CELL
 0043                   CALL TRANSP
 0044                   CALL TREAT
 0045                   CALL RESULT
 0046                   CALL GRAPH
 0047               200 CONTINUE
                  C*      RESTORE ENVIRONMENT
 0048                   CALL UNCNTL
 0049                210 CONTINUE
 0050               100 CONTINUE
 0051                   END
```

```
      SUBROUTINE SETCEL
C SETSUP WATERSHED PARAMETERS
      COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
     5F41(10),JCASE,NTA
      COMMON /CHAN/ DB(10),SLOPE(10),LENGTH(10),DEPTH(10),SIDE(10),
     1                AN(10),DISTRB(100),CONECT(10),PIPE(10)
      REAL*4 LENGTH
      INTEGER*2 CONECT
      LOGICAL*1 PIPE
      ATOT = 0.
      TLM = 0.
      WRITE(NOUT,201)
  201 FORMAT(//' WATERSHED PARAMETERS')
      DO 100 JJ = 1,NC
      DO 200 II = 1,5
      READ(5,2000) J,K,A(J,K),CN(J,K),STOR(J,K),SLR,SKN,SKS,USLE(J,K),
     1               SLOPE1,ALEN
 2000 FORMAT(2I5,F10.0,8F5.0)
      IF (A(J,K).LE. 0.) GO TO 105
      S2=1000./CN(J,K)-10.
      TLAG(J,K)=((S2+1)**0.7)*(ALEN/(1900*SQRT(SLOPE1)))
      WRITE(6,1010) TLAG(J,K)
 1010 FORMAT('0TLAG= ',F11.4)
      ATOT = ATOT + A(J,K)
      TLAG(J,K) = TLAG(J,K)/TINC
      TLM = AMAX1(TLM,TLAG(J,K))
C
C*       JUMP ON TYPE OF LAND IN CELL
C*       1,2=PERMEABLE. 3,4,5=IMPERMEABLE(BUILDUP OCCURS)
C
      GO TO (120,120,110,110,110),K
  120 WSS(J,K) = 0.
      SKR(J,K) = 0.
      W(J,K) = 0.
      GO TO 200
  110 SKR(J,K) = SKN + SKS
      WSS(J,K) = SLR/SKR(J,K)
      W(J,K) = WSS(J,K)
      GO TO 200
  105 CONTINUE
      WSS(J,K)=0.
      W(J,K)=0.
      TLAG(J,K)=0.
  200 CONTINUE
      F41(J) = 0.
      IF(A(J,4).GT.0.) F41(J) = A(J,4)/A(J,1)
  100 CONTINUE
      NLMAX = TLM
      READ(5,1020) NCHAN
 1020 FORMAT(I5)
      READ(5,1021) (PIPE(J),DEPTH(J),SLOPE(J),SIDE(J),AN(J),LENGTH(J),
     1              DB(J),CONECT(J),J=1,NCHAN)
 1021 FORMAT(4X,L1,6F10.0,I5)
 1025 FORMAT('0CHANNEL CHARACTERISTICS'/10(10X,'CHAN #= ',I5,2X,
     1          'DIAM-BWID= ',F9.3,2X,'DEPTH= ',F9.3,2X,'SLOPE= ',F6.3,
     2          2X,'SIDE SLOPE= ',F6.3,2X,'LEN= ',F8.2,2X,'MANNINGS= ',
     3          F7.4))
      RETURN
      END
```

```
FORTRAN IV G1  RELEASE 2.0            STORM            DATE = 78198        10/01/10

 0001                SUBROUTINE STORM
               C INITIATES STORM AND UPDATES WATERSHED VARIABLES
 0002                COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
                    1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
                    2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
                    3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI'150,10),
                    4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
                    5F41(10),JCASE,NTA
 0003                COMMON /SWTCH/ OPTION(10),SAMPL,SWALES
 0004                INTEGER*2 OPTION
 0005                LOGICAL*1 SWALES,SAMPL
               C INPUT STORM DATA
 0006                IF(.NOT.SAMPL) READ(NSIN,101) NTA,NTD,(CP(I),I=1,NTD)
 0007           101  FORMAT(5X,2I5,13F5.0/(15X,13F5.0))
               C COMPUTE ANTECEDENT MOISTURE CONDITIONS
 0008                TA = NTA*TINC
 0009                IF(TA.GT.120.) GO TO 100
               C
               C*        ANTECEDENT MOISTURE CONDITIONS 1,2, OR 3
               C
 0010                IF(PLAST.LE.P1) GO TO 100
 0011                IF(PLAST.LE.P2)  GO TO  120
 0012                IAMC = 3
 0013                GO TO 140
 0014           120  IAMC = 2
 0015                GO TO 140
 0016           100  IAMC = 1
 0017           140  PLAST = CP(NTD)
               C UPDATE S VALUES IN EACH CELL
 0018                DO 300 J = 1,NC
 0019                DO 200 K = 1,5
 0020                IF(A(J,K).EQ.0) GO TO 200
 0021                S2 = 1000./CN(J,K) - 10.
 0022                S(J,K) = FAC(IAMC)*S2
 0023           200  CONTINUE
               C UPDATE SOLIDS ACCUMULATION ON IMPERVIOUS AREAS IN EACH CELL
               C LINEAR BUILDUP WITH FIRST-ORDER DECAY
 0024                DO 300 K = 3,5
 0025                IF(A(J,K).EQ.0) GO TO 300
 0026                W(J,K) = WSS(J,K) + (W(J,K)-WSS(J,K))*EXP(-SKR(J,K)*TA)
 0027           300  CONTINUE
 0028                RETURN
 0029                END
```

```
            SUBROUTINE CELL
      C COMPUTES RUNOFF, SOLIDS DYNAMICS FOR EACH CELL AND TIME INCREMENT IN GIVEN STO
            COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
           1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
           2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
           3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
           4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
           5F41(10),JCASE,NTA
            REAL*4 CQ(5),DQ(5)
            DO 600 J = 1,NC
      C INITIALIZE WORKING VECTOR DQ
            DO 100 K = 1,5
        100 DQ(K) = 0.
            CPL = 0.
      C COMPUTE EXCESS PRECIPITATION
            DO 300 I = 1,NTD
            DO 200 KK = 1,5
            K = 6-KK
            IF(A(J,K).LE.0) GO TO 200
            FS(I,J,K) = 0.
            Q(I,J,K) = 0.
            TEST = CP(I)-FIA(K)*S(J,K)-STOR(J,K)
            IF(K-1) 215,215,216
      C PERVIOUS AREA ACCEPTING RUNOFF FROM IMPERVIOUS ARES
        215 TEST = TEST + CQ(4)*F41(J)
        216 IF(TEST) 210,210,220
        210 CQ(K) = 0.
            GO TO 230
        220 CQ(K) = A(J,K)*TEST*TEST/(TEST+S(J,K))
        230 Q(I,J,K) = (CQ(K)-DQ(K))
            DQ(K) = CQ(K)
        200 CONTINUE
      C COMPUTE SOLIDS WASHOFF FROM IMPERVIOUS SURFACES
            DO 400 K = 3,5
            IF(A(J,K).LE.0) GO TO 400
            RUN = Q(I,J,K)/A(J,K)
            DW = W(J,K)*(1.-EXP(-XKW*RUN))
            W(J,K) = W(J,K) - DW
            FS(I,J,K) = UNIT(1)*DW*A(J,K)
        400 CONTINUE
      C COMPUTE EROSION FROM PERVIOUS AREA
            DO 450 K = 1,2
            IF(A(J,K).LE.0) GO TO 450
            FS(I,J,K) = UNIT(2)*USLE(J,K)*((Q(I,J,K)*Q(I,J,K)/TINC)**.56)
        450 CONTINUE
            PREC = (CP(I)-CPL)
            CPL = CP(I)
      C ADD SOLIDS INFLUX FROM IMPERVIOUS AREA
            IF(A(J,1).LE.0) GO TO 460
            TEMP=Q(I,J,4)+ PREC*A(J,1)
            IF (TEMP.EQ.0) GO TO 460
            FS(I,J,1)=FS(I,J,1)+FS(I,J,4)*Q(I,J,1)/TEMP
        460 CONTINUE
      C END LOOP AROUND STORM EVENT
        300 CONTINUE
      C END LOOP AROUND CELLS
        600 CONTINUE
            RETURN
            END
      SUBROUTINE TREAT
C STORES AND/OR TREATS POLLUTOGRAPH BELOW POINT A
C IGNORES OVERLAP OF STORMS
      COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
     5F41(10),JCASE,NTA
      REAL KTS,KTT
C SET INITIAL CONDITIONS
      VS = 0.
      SS = 0.
      DO 200 I = 1,NLST
      QD(I) = 0.
      FSD(I) = 0.
      FSR(I) = 0.
      IF(QI(I,1).LE.0.) GO TO 200
  160 VN = VS + QI(I,1)
C CHECK FOR FILLED STORAGE FACILITY
      IF(VN-VSMAX) 110,120,120
C NOT FILLED
  110 SS = SS + FSI(I,1)
      VS = VS + QI(I,1)
      GO TO 200
C FILLED
  120 DV = VSMAX - VS
      VS = VSMAX
      SS = SS + DV*FSI(I,1)/QI(I,1)
      QSB = QI(I,1)-DV
      FSB = QSB*FSI(I,1)/QI(I,1)
C CHECK TREATMENT CAPACITY
      QD(I) = QSB
      IF(QSB-QTMAX) 130,130,140
  130 FSD(I) = FSB*(1.-KTR)
      FSR(I) = FSB - FSD(I)
      GO TO 200
C TREATMENT CAPACITY EXCEEDED
  140 FTR = QTMAX/QSB
      FSD(I) = FSB*(1.-FTR*KTR)
      FSR(I) = FSB*FTR*KTR
  200 CONTINUE
      RETURN
      END
```

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            SUBROUTINE RESULT
      C PRINTS RESULTS FOR LAST STORM
            COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
           1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
           2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
           3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
           4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
           5F41(10),JCASE,NTA
            REAL KTS,KTT
            WRITE(6,101) IS,NTA,NTD,NLST,IAMC ,JCASE
        101 FORMAT('1'' STORM:',I5,' ANTECEDENT DRY PD:',I5,' PRECIP DURATION'
           1,': ',I5,' EVENT DURATION: ',I5,' ANTE MOISTURE COND: ',I5,
           2' CASE: ',I5)
            WRITE(6,103)
        103 FORMAT(/'   I       P       CP      QI      SQI      FSI      SSI',
           1'      CI      QD      SQD      FSD      SSD      CD      FSR      SSR'
           2)
            DO 200 I = NTD,NLST
        200 CP(I) = CP(NTD)
            POLD = 0.
            SQI = 0.
            SSI = 0.
            SQD = 0.
            SSD = 0.
            SSR = 0.
            DO 100 I = 1,NLST
            CD = 0.
            CI = 0.
            IF(QD(I)) 110,110,120
        120 CD = UNIT(5)*FSD(I)/QD(I)
        110 IF(QI(I,1).LE.0.) GO TO 130
            CI = UNIT(5)*FSI(I,1)/QI(I,1)
        130 SQI = SQI + QI(I,1)
            SSI = SSI + FSI(I,1)
            SQD = SQD + QD(I)
            SSD = SSD + FSD(I)
            SSR = SSR + FSR(I)
            P = CP(I) - POLD
            WRITE(6,102)I ,P,CP(I),QI(I,1),SQI,FSI(I,1),SSI,CI,QD(I),SQD,
           1   FSD(I),SSD,CD,FSR(I),SSR
        102 FORMAT(I4,14F8.3)
            POLD = CP(I)
        100 CONTINUE
      C STORED VOLUME AND SOLIDS
            VS = VS + SQD
            FR = SSR + KTS*SS
            SS = SSD + (1.-KTS)*SS
            EF = FR/SSI
            WRITE(NOUT,104) VS,SS,FR,EF
        104 FORMAT(//' EVENT TOTALS INCLUDING STORED VOLUME AND SOLIDS'/
           1' DISCHARGE VOLUME = ',F10.2/' DISCHARGE SOLIDS = ',F10.2/
           2' REMOVED SOLIDS = ',F10.2/' STORAGE/TREATMENT EFFICIENCY = ',
           3F10.3)
            END
      SUBROUTINE CONTRL
C
C*       CALCULATES EFFECTS OF CONTROL OPTIONS
C
      COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
     5F41(10),JCASE,NTA
      COMMON /SWTCH/ OPTION(10),SAMPL,SWALES
      COMMON /SAV/ SAVE(10,5),SAVE2(10,5),SAVE3(10,5),SAVE4(10,5)
      INTEGER*2 OPTION
      LOGICAL*1 SWALES,SAMPL
      SWALES=.FALSE.
      READ(5,1000) OPTION
 1000 FORMAT(10I5)
      DO 50 I=1,NC
      DO 50 J=1,5
      SAVE(I,J)=CN(I,J)
      SAVE2(I,J)=A(I,J)
      SAVE3(I,J)=USLE(I,J)
      SAVE4(I,J)=STOR(I,J)
   50 CONTINUE
      DO 220 I=1,10
      IF(OPTION(I).LE.0) GO TO 250
      K=OPTION(I)
      GO TO (110,120,130,140,150,160,170),K
C
C*       UNUSED OPTION
C
      WRITE(6,1010) OPTION(I)
 1010 FORMAT('0**NO SUCH OPTION NUMBER**', 1X,I5)
      GO TO 220
C
C*       POROUS PAVEMENT
C
  110 DO 112 J=1,NC
  112 CN(J,5)=CN(J,1)*0.8
      GO TO 220
C
C*       VEGETATTIVE COVER
C
  120 DO 122 J=1,NC
      CN(J,1)=30
      CN(J,2)=30.
      USLE(J,1)=USLE(J,1)*0.5
  122 USLE(J,2)=USLE(J,2)*0.5
      GO TO 220
C
C*       ROOF DRAIN DISCONNECT
C
  130 DO 132 J=1,NC
```

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 0034                      A(J,4)=A(J,4)+A(J,3)*0.8
 0035                  132 A(J,3)=A(J,3)*0.2
 0036                      GO TO 220
                  C
                  C*       ON-LOT STORAGE
                  C
 0037                  140 DO 142 J=1,NC
 0038                  142 STOR(J,1)=0.07
                  C
 0039                      GO TO 220
                  C
                  C*        SWALES
                  C
 0040                  150 SWALES=.TRUE.
 0041                      GO TO 220
                  C
                  C*    SOIL TYPES
                  C
 0042                  160 DO 162 J=1,NC
 0043                      CN(J,1)=85.
 0044                  162 CN(J,2)=85.
                  C
                  C
 0045                  170 CONTINUE
 0046                  220 CONTINUE
 0047                  250 CONTINUE
 0048                      WRITE(6,1030)
 0049                 1030 FORMAT('0**END OF CONTROL MEASURE CHANGES**')
 0050                      RETURN
 0051                      END
```

```
               SUBROUTINE UNCNTL
         C*        RESTORES ORIGINAL ENVIRONMENT
               COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
              1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
              2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
              3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
              4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
              5F41(10),JCASE,NTA
               COMMON /SWTCH/ OPTION(10),SAMPL,SWALES
               COMMON /SAV/ SAVE(10,5),SAVE2(10,5),SAVE3(10,5),SAVE4(10,5)
               INTEGER*2 OPTION
               LOGICAL*1 SWALFS,SAMPL
               DO 50 I=1,NC
               DO 50 J=1,5
               CN(I,J)=SAVE (I,J)
               A(I,J)=SAVE2(I,J)
               USLE(I,J)=SAVE3(I,J)
               STOR(I,J)=SAVE4(I,J)
            50 CONTINUE
               SWALES=.FALSE.
               RETURN
               END
```

```
0001            SUBROUTINE GRAPH
          C
0002            COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
               1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
               2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
               3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
               4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
               5F41(10),JCASE,NTA
0003            COMMON /SWTCH/ OPTION(10),SAMPL,SWALES
0004            COMMON /TITL/ TITLE(20)
0005            INTEGER*2 OPTION
0006            LOGICAL*1 SWALES,SAMPL
          C
          C
0007            LOGICAL*1 QSYM/'*'/,PSYM/'P'/,SSYM/'S'/,BLANK/' '/,DSYM/'2'/
0008            LOGICAL*1 QLINE(121),FLAG
0009            INTEGER*2 QPOS,SPOS,PPOS
0010            REAL*4 PINC(3),SINC(11),QINC(11)
          C
0011            FLAG=.FALSE.
          C*             GET SCALES
          C
0012            QMAX=0.5
0013            SMAX=120.
0014            PMAX=3.5
0015            QINCR=QMAX/100*10.
0016            SINCR=SMAX/100*10.
0017            PINCR=PMAX/20.*10.
0018            TINCR=0.0
0019            QSCALE=QMAX/99
0020            SSCALE=SMAX/99
0021            PSCALE=PMAX/20
0022            QINC(1)=0.
0023            SINC(1)=0.
0024            PINC(3)=0.
0025            PINC(2)=PINCR
0026            PINC(1)=PINCR+PINCR
0027            DO 25 I=2,11
0028            QINC(I)=QINCR+QINC(I-1)
0029            SINC(I)=SINCR+SINC(I-1)
0030         25 CONTINUE
          C
          C*             WRITE TOP HEADER
          C
0031            WRITE(6,1000) TITLE
0032       1000 FORMAT('1',10X,20A4)
0033            WRITE(6,2000)
0034       2000 FORMAT('0CONTROL OPTIONS SELECTED= ' )
0035            DO 30 I=1,10
0036            K=OPTION(I)
0037            IF(K.EQ.0) GO TO 30
0038            FLAG=.TRUE.
0039            GO TO (31,32,33,34,35,36,30,30,30,30),K
```

```
      GO TO 30
   31 WRITE(6,2001)
 2001 FORMAT(26X,'POROUS PAVEMENT')
      GO TO 30
   32 WRITE(6,2002)
 2002 FORMAT(26X,'VEGETATIVE COVER')
      GO TO 30
   33 WRITE(6,2003)
 2003 FORMAT(26X,'ROOF-DRAINS DISCONNECTED')
      GO TO 30
   34 WRITE(6,2004)
 2004 FORMAT(26X,'ON-LOT STORAGE')
      GO TO 30
   35 WRITE(6,2005)
 2005 FORMAT(26X,'SWALES')
      GO TO 30
   36 WRITE(6,2006)
 2006 FORMAT(26X,'IMPERVIOUS SOILS')
   30 CONTINUE
      IF(.NOT.FLAG) WRITE(6,2010)
 2010 FORMAT(26X,'NONE')
      WRITE(6,1005)
      WRITE(6,1015) PINC
 1015 FORMAT(109X,2(F3.1,7X),F3.1)
      WRITE(6,1006)
 1005 FORMAT(15X,'FLOW & SOLIDS-->',65X,'<-- CUMULATIVE RAIN')
 1006 FORMAT(10X,'+',24('....+'))
C
C*              LOOP OVER TIME INTERVALS
C
      DO 100 I=1,NLST
C
C*              BLANK LINE
C
      DO 50 J=1,121
   50 QLINE(J)=BLANK
C
C*              GET POSITIONS
C
      IF(QI(I,1).GT.QMAX)     QI(I,1)=QMAX
      IF(FSI(I,1).GT.SMAX) FSI(I,1)=SMAX
      QPOS=INT(QI(I,1)/QSCALE)+1
      SPOS=INT(FSI(I,1)/SSCALE)+1
      PPOS=INT(CP(I)/PSCALE)+1
      PPOS=122-PPOS
C
      DO 77  J=1,QPOS
   77 QLINE(J)=QSYM
      QLINE(SPOS)=SSYM
      QLINE(PPOS)=PSYM
C
C
      IF(I.EQ.1) WRITE(6,1045) TINCR,QLINE
 0081                 IF((I-(I/5)*5).EQ.0) GO TO 75
 0082                 WRITE(6,1050) QLINE
 0083                 GO TO 80
 0084              75 WRITE(6,1045) TINCR,QLINE
 0085            1045 FORMAT(4X,F5.2,'+',121A1,'|')
 0086            1050 FORMAT(9X,'|',121A1,'|')
 0087              80 CONTINUE
 0088                 TINCR=TINCR+TINC
            C
            C*              END OF LOOP OVER TIME DELTAS
            C
 0089             100 CONTINUE
            C
            C*              WRITE TRAILER
            C
 0090                 WRITE(6,1006)
 0091                 WRITE(6,1010) QINC
 0092            1010 FORMAT(9X,11(F3.1,7X))
 0093                 WRITE(6,1020) SINC
 0094            1020 FORMAT(7X,11(F5.1,5X))
 0095                 WRITE(6,1005)
            C
 0096                 WRITE(6,1090) QSCALE,QMAX,SSCALE,SMAX,PSCALE,PMAX
 0097            1090 FORMAT(//10X,'FLOW INCREMENTS= ',F10.4/
                 1            10X,'FLOW MAX=         ',F10.4/
                 2            10X,'SOLIDS INCREMENTS= ',F10.4/
                 3            10X,'SOLIDS MAX=        ',F10.4/
                 4            10X,'RAIN(CUM.)=       ',F10.4,' INCHES'/
                 5            10X,'RAIN (MAX CUM.)= ',F10.4,' INCHES')
            C
 0098                 RETURN
 0099                 END
```

```
      SUBROUTINE TRANSP
C CONSTRUCTS HYDROGRAPH AND POLLUTOGRAPH AT POINT A
      COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
     5F41(10),JCASE,NTA
      COMMON /CHAN/ DB(10),SLOPE(10),LENGTH(10),DEPTH(10),SIDE(10),
     1               AN(10),DISTRB(100),CONECT(10),PIPE(10)
      COMMON /SWTCH/ OPTION(10),SAMPL,SWALES
      REAL*4 QOUT(100,10),Q5(100,10),FSOUT(100,10),F5(100,10),N$,LENGTH
      INTEGER*2 OPTION,CONECT
      LOGICAL*1 PIPE,PIPE2
      LOGICAL*1 SWALES,SAMPL
      NLST = NTD + NLMAX
      DO 10 I=1,100
      DO 5 J=1,NC
      FSI(I,J)=0.
      QOUT(I,J)=0.
      FSOUT(I,J)=0.
    5 QI(I,J)=0.
   10 CONTINUE
      DO 100 I = 1,NTD
      DO 100 J = 1,NC
      DO 95 K=1,5
      IF (A(J,K).LE.0) GO TO 95
      L = TLAG(J,K)
      L=I+L
      QI(L,J)=QI(L,J)+Q(I,J,K)
      FSI(L,J)=FSI(L,J)+FS(I,J,K)
  95  CONTINUE
 100  CONTINUE
C
C*        LOOP THROUGH LIST OF CELLS
C*        ARRAY CONNECT HOLDS UPSTREAM-DOWNSTREAM CONNECTIONS
C*        ADD HYDROGRAPHS BY STARTING WITH UPSTREAM END, FLOWS.
C*        CALL TRANSPORT AND GET OUTPUT HYDROGRAPH, QOUT
C*        ADD THIS TO NEXT Q(TIME, CELL) TO GET NEXT INPUT HYDROGRAPH,
C*        QIN.  ETC.
C
      MAXLST=0
      DO 140 J=1,NC
      NODE=CONECT(J)
C
      DB1=DB(NODE)
      Z=SIDE(NODE)
      S1=SLOPE(NODE)
      Y=DEPTH(NODE)
      AL=LENGTH(NODE)
      N$=AN(NODE)
      IF(SWALES) N$=N$*1.5
      PIPE2=PIPE(NODE)
      IF(J.EQ.1) NODE1=NODE
C
      IF(.NOT.PIPE2) GO TO 110
      AREA=Y*(DB1+Z*Y)
C
C*       P1 IS WETTED PERIMETER
C
      P1=DB1+2.*Y*SQRT(1+Z*Z)
      GO TO 120
C
C*       CIRCULAR CROSS-SECTION
C
  120 QCON=1.486/N$*AREA**1.667*(SQRT(S1))/P1**.667
  110 AREA=3.14159*DB1/4.
      P1=3.14159/DB1
      N=0
      Q1=0.
      DO 125 K=1,NLST
C
C*       CHECK FOR ZERO FLOWS AND OVERFLOW
C
      IF(QI(K,NODE).EQ.0) GO TO 125
      IF(QI(K,NODE).LT..00001) GO TO 125
      N=N+1
      IF(QI(K,NODE).LE.QCON) GO TO 124
      WRITE(6,1011) NODE,QI(K,NODE)
 1011 FORMAT('0OVERFLOW IN CHANNEL ',I5,'  FLOW= ',F10.4)
      QI(K,NODE)=QCON
  124 Q1=Q1+QI(K,NODE)+QOUT(K,NODE1)
C*        ACCUMULATE FLOWS
C
      QI(K,NODE)=QI(K,NODE)+QOUT(K,NODE1)
      FSI(K,NODE)=FSI(K,NODE)+FSOUT(K,NODE1)
  125 CONTINUE
C        GET AVERAGE VOLUME
C
      IF(N.GT.0) Q1=Q1/N
C*       ROUTE USING THIS AVERAGE V
C
      CALL ROUTE(PIPE2,DB1,Z,Y,N$,S1,AL,Q1,VEL,TI)
      C=VEL/(VEL+1.7)
      TI=TI*C
      CS=1.
      IF(TI.GT.0.) CS=1.-(1.-C)**((TINC+0.5*TI)/(1.5*TI))
      QQ=0.
      FF=0
      DO 127 K=2,NLST
      KK=K-1
      QOUT(K,NODE)=(1-CS)*QQ+CS*QI(KK,NODE)
      FSOUT(K,NODE)=(1-CS)*FF+CS*FSI(KK,NODE)
      FF=FSOUT(KK,NODE)
  127 QQ=QOUT(K,NODE)
      QOUT(1,NODE)=0.
      FSOUT(1,NODE)=0.
      DO 130 K=1,NLST
      F5(K,NODE)=FSOUT(K,NODE)
  130 Q5(K,NODE)=QOUT(K,NODE)
      KC=TI/TINC+0.5
      DO 135 K=1,NLST
      KI=K+KC
      FSOUT(KI,NODE)=F5(K,NODE)
  135 QOUT(KI,NODE)=Q5(K,NODE)
      IF(KC.LE.0) GO TO 138
      DO 137 K=1,KC
      FSOUT(K,NODE)=0.
  137 QOUT(K,NODE)=0.
  138 CONTINUE
C
C*         END OF LOOP OVER CELLS
C
      IF(MAXLST.LT.KC) MAXLST=KC
      NODE1=NODE
  140 CONTINUE
      NLST=NLST+MAXLST
      WRITE(6,8050) NLST,MAXLST
 8050 FORMAT('0END TIME =',I5,' MAX TRAVEL TIME= ',I5)
      DO 200 I=1,NLST
      QI(I,1)=        QOUT(I,NODE)
      FSI(I,1)=FSOUT(I,NODE)
  200 CONTINUE
      RETURN
      END
      SUBROUTINE ROUTE(PIPE,DB,SIDE,DEPTH,MANING,SLOPE,LENGTH,Q,VEL,TI)
C
      REAL*4 MANING,LENGTH
      LOGICAL*1 PIPE
C
      TI=0.
      VEL=0.
      DY=DEPTH/40.
      N=0
C*
C*       N IS INDEX FOR OVERFLOW CONDITION
      IF(.NOT.PIPE) GO TO 20
C
C*       TRAPEZOIDAL CHANNEL
    5 AREA=DEPTH*(DB+SIDE*DEPTH)
C*       P IS WETTED PERIMETER
      P=DB+2.*DEPTH*SQRT(1+SIDE*SIDE)
C
C
      Q1=(1.486/MANING)*AREA**1.667*(SLOPE**0.5)/(P**0.667)
      IF(Q.GE. Q1) GO TO 10
      Q2=Q1
C
C*       ITERATE ON DEPTH
C
      DEPTH=DEPTH-DY
      IF(DEPTH.LE.0) RETURN
      GO TO 5
   10 IF(N.NE.1) GO TO 15
      DEPTH=DEPTH*3.
      WRITE(6,1000) DEPTH
 1000 FORMAT('0**FLOW EXCEEDS CHANNEL,DEPTH= ',F8.4)
      GO TO 5
C
C*       GOT FINAL HYDRAULIC RADIUS
C
   15 DEPTH=DEPTH+DY-(Q2-Q)/(Q2-Q1)*DY
      AREA=DEPTH*(DB+SIDE*DEPTH)
      P=DB+2.*Y*SQRT(1+SIDE*SIDE)
      Q1=(1.486/MANING)*AREA**1.667*(SLOPE**0.5)/(P**0.667)
      GO TO 40
C
C*       CIRCULAR PIPE SECTION
C
   20 TH=2.*3.14159
      DTH=TH/40.
   25 AREA=(TH-SIN(TH))*(DB*DB)/8.
      N=N+1
      P=TH*DB*0.5
      Q1=(1.486/MANING)*AREA**1.667*(SLOPE**0.5)/(P**0.667)
      IF(Q.GE.Q1) GO TO 28
      Q2=Q1
      TH=TH-DTH
      IF(TH.LE.0) RETURN
      GO TO 25
   28 IF(N.NE.1) GO TO 30
      DB=3*DB
      WRITE(6,1015) DB
 1015 FORMAT('0** PIPE  DIAM TRIPLED, CHANNEL OVERFLOW, DIAM= ',F8.4)
      GO TO 25
C
C*       GOT FINAL HYDRAULIC RADIUS
C
   30 TH=TH+DTH-(Q2-Q)/(Q2-Q1)*DTH
      AREA=(TH-SIN(TH))*DB*DB/8.
      P=TH*DB*0.5
      Q1=(1.486/MANING)*AREA**1.667*(SLOPE**0.5)/P**0.667
      DEPTH=DB*(1.-COS(TH/2.))*0.5
C*       VELOCITY
   40 VEL=Q1/AREA
C*       TI= TIME SHIFT IN HOURS
      TI=LENGTH/VEL/3600.
      IF(N.EQ.1) WRITE(6,1055)
 1055 FORMAT('0**CHANNEL OVERFLOW AT SOME POINT IN TIME**')
      RETURN
      END
```

```
FORTRAN IV G1  RELEASE 2.0          SAMPLE            DATE = 78198          10/01/10

 0001                 SUBROUTINE SAMPLE(VOLUME)
 0002                 COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
                     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
                     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
                     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
                     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
                     5F41(10),JCASE,NTA
 0003                 COMMON /CHAN/ DB(10),SLOPE(10),LENGTH(10),DEPTH(10),SIDE(10),
                     1             AN(10),DISTRB(100),CONECT(10),PIPE(10)
 0004                 INTEGER*2 CONECT
 0005                 LOGICAL*1 PIPE
             C
             C*          RETURNS RANDOM VOLUME INTERVAL AND SITRIBUTION
 0006                 REAL*8 SEED
 0007                 REAL*4 RESULT(1)
 0008                 READ(5,1005) NTD,NTA,VOLUME
 0009           1005 FORMAT(2I5,F10.0)
 0010                 SEED=0.817585
 0011                 CALL GGUB(SEED,1,RESULT)
             C
 0012                 RESULT(1)=RESULT(1)/10.
 0013                 VOLUME=(VOLUME+(RESULT(1)-0.05))/100
 0014                 WRITE(6,1000) VOLUME
 0015           1000 FORMAT('0RANDOM VOLUME= ', F10.4)
 0016                 READ(5,1010) (DISTRB(I),I=1,NTD)
 0017           1010 FORMAT(16F5.0)
 0018                 RETURN
 0019                 END
```

```
      SUBROUTINE SETSTM(SEED,VOLUME)
      COMMON P1,P2,TINC,FAC(3),NC,PLAST,XKW,NLMAX,ATOT,FIA(5),NSTO,
     1NIN,NSIN,NCIN,A(10,5),STOR(10,5),CN(10,5),WSS(10,5),TLAG(10,5),
     2USLE(10,5),SKR(10,5),NTD,CP(150),NTS,NLST,W(10,5),Q(100,10,5),
     3FS(100,10,5),VSMAX,VTMAX,QSMAX,QTMAX,KTS,KTT,UNIT(10),QI(150,10),
     4FSI(150,10),QD(150),FSD(150),FSR(150),IAMC,NOUT,S(10,5),SS,VS,IS,
     5F41(10),JCASE,NTA
      COMMON /CHAN/ DB(10),SLOPE(10),LENGTH(10),DEPTH(10),SIDE(10),
     1               AN(10),DISTRB(100),CONECT(10),PIPE(10)
      LOGICAL *1 PIPE
      INTEGER*2 CONECT
      REAL*4 LENGTH
      REAL*4 RESULT(100)
      REAL*8 SEED
C
C
C
C*       SEE IF WERE USING CARDS OR MONTE CARLO
C
      WRITE(6,1000)
 1000 FORMAT('0** MONTE CARLO SIMULATION **')
C
C*       GET RANDOM NUMBERS FROM UNIFORM DIT.
C
      CALL GGUB(SEED,100,RESULT)
      DO 10 I=1,150
   10 CP(I)=0.
      DO 100 I=1,100
      DO 50 J=2,NTD
      IF(RESULT(I).LT.DISTRB(J).AND.RESULT(I).GE.DISTRB(J-1))CP(J)=CP(J)
     1                                                      +VOLUME
   50 CONTINUE
      IF(RESULT(I).LE.DISTRB(1)) CP(1)=CP(1)+VOLUME
  100 CONTINUE
C
      DO 200 I=2,NTD
  200 CP(I)=CP(I)+CP(I-1)
C
      WRITE(6,1010) (CP(I),I=1,NTD)
 1010 FORMAT('0PRECIPITATION= ', 8(2X,F6.4,5X))
      RETURN
      END
```

APPENDIX D[1]

PERFORMANCE OF INNOVATIVE DESIGNS FOR STORMWATER MANAGEMENT

As discussed in Section 9 of this report, innovative site and roadway designs were recently implemented in two residential developments in Southeastern Massachusetts, Trout Farm and Bowker Woods. The roadways and housing unit layouts were designed to manage stormwater in non-traditional ways. This appendix describes the actual roadway designs used for these two sites and assesses their performance after one year of construction and use. Also assessed are the infiltration characteristics of the sites. For a more detailed description of the sites, refer to the case studies in Section 9 of the main report.

ROAD DESIGNS

Given the highly permeable soil conditions at the Trout Farm site in Duxbury, Massachusetts, the roadway was designed with a 4-inch porous macadam surface placed upon a 6-inch gravel base. The subgrade preparation conformed to the Commonwealth of Massachusetts, Department of Public Works Standard Specifications, Section 170.16, and the gravel base to MDPW Section 405. The porous macadam consisted of MDPW 1 1/2 inch crushed stone gradation, 2 gallons per square yard of AC-10 liquid asphalt, and 3/8 inch keystone.

The roadway has minimum shoulders for off-grading with clearing limited to close to the paved surface. The road follows closely the natural contours of the land; only a few significant cuts and fills were made. Paved surfaces for two-way roads are 18 feet wide. One-way traffic sections, such as loop cul-de-sacs, are 12 feet wide. Turn-outs for emergency vehicles were designed at hydrants and within cul-de-sacs.

At the Bowker Woods site in Norwell, Massachusetts, the generally wet soils are quite unsuitable for construction purposes. Where the soils did not conform to the MDPW standards, a gravel base course was placed over the prepared, excavated subgrade. The macadam surface is 8 inches of 1 1/2 inch crushed stone, penetrated and choked with keystone as described above. The gravel base is pitched towards a 12-inch perforated aluminum underdrain which sits in a 3/4-inch crushed stone filter directly contacting the macadam surface. The underdrain carries the water infiltrating through the macadam surface to a small surface retention pond which dries seasonally as the water table drops.

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[1] This appendix is based on a document prepared by BSC Engineering, Inc. under subcontract to Meta Systems.

By placing the road in a slight cut just below the original ground level it is possible to intercept runoff and spring seepage from upland areas, filter it through the road and the underdrain envelope, and then discharge it to a small pond. After filtering, settling, and buffering, the runoff flows to an existing wetland.

As in Trout Farm, minimal clearing was performed. The width of the paved surface is 16 feet including shoulder turn-outs. The road follows existing contours and is not centered in the dedicated right-of-way. However, it is entirely contained within the 50 foot right-of-way layout.

Roadway Performance Observations During Construction and Use

There has now been some actual experience with these roads. They have been observed both during their construction and during the period of heavy use when the homes in the developments were being constructed. They have both gone through one winter. As would be expected, the keystone has become visually worn in the tire tracks. This is particularly evident on the one sharp curve in Trout Farm. Snow plowing has not been a major problem.

At only one location in Trout Farm has there been any lack of infiltrative capacity. This is at a sharp turn at the entrance that receives heavy construction loads under turning stresses. Here there have been puddles after heavy rains. However, everywhere else the road has remained dry under all precipitation and snow melt conditions. Although Trout Farm is now approximately 40 percent built and occupied, there is still no apparent overland discharge to the brook which divides the site other than that which falls directly on the stream or its banks, as it would have been had the site been left in its natural state.

At Bowker Woods this spring, during the snow melt, small seepage streams were observed running overland to the road and then disappearing through the pavement. Even under these conditions very little of the road became wetted; all of the runoff appears to be intercepted within the area about six inches in from the edge of the pavement. After flowing through the road and the settling pond to the wetland, this runoff discharge continues to be very small and of apparently high quality.

It must be noted that the reduced asphalt content of the roadway pavement does reduce its strength. While this is not a problem for even loads, such as redi-mix concrete trucks, pavement strength is a direct function of the gravel base grading and compaction. Where these reduced asphalt pavements have been constructed in a slight embankment above the original ground level and have little or no end restraint, it has been observed that wheel loads can depress the edge of the pavement. There seems to be no change in drainage performance of these edge depressions, however.

Site Infiltration Performance Observations

Since the years 1974 to 1975 winter frost observations have been made at two sites in Southeastern Massachusetts: an undeveloped coastal plain, pitch pine and scrub oak forest site in Plymouth; and Trout Farm.

At the Plymouth site during the period of February 19 through 21, 1975, a rainfall simulation was conducted with a cranberry bog irrigation system on the frozen snow-covered woods. Rainfalls simulated ranged from 13 inches in 4 hours to 17 inches in 24 hours. Frost depths in the wooded sections were 1 1/4 to 1 1/2 inches and were 15 inches in the grassed shoulder of an old cart path.

These depths are similar to the frost depths which have been measured during three winters at Trout Farm. There, in the undisturbed portion of the site, frost depths ranged from 1 1/4 to 1 1/2 inches in 1974-1975 to 1 3/4 to 2 inches in 1977-1978. This observation period has included two of the most severe winters in recent history. Essentially, in these well-drained outwash soils, only the fresh humus layers actually freeze.

It is not possible to excavate, grade, or compact soils such as these without dramatically changing their structure and frost characteristics. However, this alteration is limited to almost the exact area of disturbance, even when clearing alters wind, sunlight exposures and microclimates. At Trout Farm frost in the backfilled areas of the houses was 22 to 24 inches deep by the end of January. The road base was also frozen to an estimated depth of 20 inches. However, 3 feet away from the pavement in a graded shoulder the frost was 7 1/4 inches, and the frost was 2 5/8 inches 6 feet away. This compared to 1 3/4 to 2 inches in undisturbed areas.

From these observations it can be concluded that narrow roads, minimal site work, and limited clearing for housing construction greatly enhance site surficial geologic characteristics. Continuous irregular bands of undisturbed land left throughout the construction site can provide natural runoff interceptors. During winter and summer their high infiltration capacities are sufficient to eliminate overland flow to a watercourse. Furthermore, as at Bowker Woods, the roads can also act as such interceptors if they are properly located on the landscape.

APPENDIX E

COST ALLOCATION IN MULTIPURPOSE PROJECTS

Unlike traditional stormwater drainage systems, innovative stormwater management projects are generally multipurpose projects, meeting such objectives as improved water quality, improved flood control, more pleasing aesthetic surroundings, lower operation and maintenance costs, etc. As such, it may be in the interest of more than one organization or government agency to promote their implementation. If more than one level of government or more than one government agency becomes involved in promoting and financing innovative stormwater management techniques, the question of appropriate cost allocation may become important. This appendix addresses the question of cost allocation by explaining general principles which could be followed, outlining some rules which are now used to guide such decisions, and measuring benefits accruing to multipurpose projects.

COST ALLOCATION IN MULTIPURPOSE PROJECTS

Whenever the financial responsibility for a project is divided, its total cost must be distributed among the responsible groups. Cost allocation can be defined as the assignment of costs of a multiple purpose project to individual purposes. Most cost allocation solutions attempt to meet some combination of the following two objectives (Regan, 1964):

- Efficient use of resources;
- Promotion of incidence and distribution policies

Various arrangements attempt to minimize conflicts among these two objectives. S.V. Ciriacy-Wantrup (1964), after reviewing numerous discussions of the subject written by engineers, lawyers, accountants, and economists, reports that most conclude that cost allocation is more or less arbitrary. Although this conclusion may be generally valid, there are certain principles which can form a basis upon which to develop a cost allocation procedure. We will first examine those principles from economics, law and public finance which apply to the problem of cost allocation. This review will provide background for an examination of alternative rules which are commonly used to allocate costs. We will conclude with a discussion of the difficulties inherent in applying one of the most desirable cost allocation rules.

Principles

In discussing common property resources and users of such resources who engage in activities which have beneficial or harmful effects on other users of the common resources (externalities), economists rely on the principle of efficiency to determine what the optimum allocation of resources should be. The most efficient use of resources is that which maximizes the net value of production. Ronald Coase, in "The Problem of Social Cost" (1960), develops what has become known as the Coase Theorem regarding activities involving externalities. He demonstrates that the optimal allocation of resources will occur if the actors are able to negotiate to their mutual advantage at no cost. Under this condition the same result will be obtained no matter which of the joint cost causers is initially charged with the costs. That is, an arrangement will be negotiated so that either the damages will compensate the sufferer in order to be able to continue his activity or the potential sufferer will pay the damage to desist or alter his activity.

However, in the real world negotiations, even market transactions, are not completely costless (there are selling costs, for example). Especially where common property such as a water resource is involved, there are such difficulties as arranging for bargaining among large numbers of people or the problem of excluding freeloaders, etc. Here, the recommendation of Coase and others (see Calabresi, 1968, and Turvey, 1963) is that the least costly alternative measures (market transaction, taxation liability rules), including no charge at all, be chosen. To put it in efficiency terms, when the costs of alternative arrangements are taken into account, a rearrangement should only be undertaken when the resulting increase in the value of production is greater than the costs involved in bringing it about. Thus the cost of limiting environmental damage should be made to fall wherever it can be borne most cheaply.

Many economists, such as those whose ideas are discussed above, avoid judgements regarding the distributional consequences of assigning liability in the cheapest possible way. A choice regarding income distribution is generally felt to be outside the province of economics. Frank I. Michelman, in his essay, "Property, Utility, and Fairness: Comments on the Ethical Foundations of 'Just Compensation' Law" (1967), tackles this weighty problem. He discusses the situation in which society decides to reallocate resources so as to increase total welfare (meet the efficiency objective), and consequently some members of society become less well off than they were before. The loss incurred by these people is the opportunity cost of the allocation decision. The question Michelman attempts to answer is whether such costs should remain where they fall initially or whether compensation should be paid and the costs explicitly distributed according to the tax structure or some other principle. He appeals to utilitarian theories of property as a collection of rules which are accepted as governing the exploitation and enjoyment of resources. These rules form the basis of people's expectations. Therefore, he concludes that compensation should be paid in cases where if it were not paid, it would be critically demoralizing to members of society.

In any resource reallocation decision there are efficiency gains to be had, demoralization costs, and what Michelman terms "settlement costs," (the costs incurred in compensating those who are made less well off). Michelman's test for a reallocation decision is that the measure should be rejected if efficiency gains are less than demoralization costs or settlement costs and that compensation should be paid when demoralization costs are greater than settlement costs (or should be paid up to the point where the cost of compensating the remaining losers is greater than the remaining demoralization costs). In applying this rule Michelman uses the Rawlsiar concept of fairness: an arrangement is fair if it is consistent with principles which can be agreed upon by every member of the group, even the one who is least well off under any rule. According to this view, compensation practice should reconcile efficiency with the protection of expectations of fairness.

Musgrave and Musgrave (1976) also grapple with the definition of fairness in their discussion of the objective of equity as the basic criterion for designing an appropriate tax structure. An equitable tax structure is defined as one in which each tax payer contributes his "fair share" to the cost of government. The Musgraves discuss the approaches to defining "fair share"; one approach involves the benefit principle, in which each tax payer contributes according to the benfits he receives from public services. Examples of benefit taxes are fees, user charges, and tolls. The application of this approach is limited by the difficulties involved in identifying the beneficiaries of many public services.

The other approach applies the ability-to-pay principle, in which taxation is independent of the government's expenditure policy. According to this definition, a given revenue is needed and each taxpayer contributes in line with his ability to pay. This requires that equal taxes will be paid by persons with equal abilities to pay (horizontal equity) and unequal taxes to be paid by those in unequal positions (vertical equity). Since John Stuart Mill, equitable treatment has been viewed as involving an equal sacrifice or loss of welfare. If measured in terms of income, the ability-to-pay of persons with equal income will be equal. For those with unequal incomes, the answer is less obvious. The Musgraves describe three rules which could be chosen to define equal sacrifices: equal absolute sacrifice, in which the loss of income from each person entails an equal loss of utility dependent on each one's shape of the marginal utility of income curve; equal proportional sacrifice, in which each pays an equal proportion of income; equal marginal sacrifice, in which the marginal utility of the income given up by each is the same and which also results in the least total sacrifice. Thus there are numerous choices to be made even in following what appears to be a straightforward allocation principle.

Common Cost Allocation Rules

As mentioned at the outset, it is necessary to divide the cost of a multipurpose water resources project among the respective project purposes. For example, costs for flood control must be distinguished from those for water quality. Before discussing some commonly used rules for cost allocation, we will provide some necessary definitions. Direct costs are the costs of each distinct physical portion of the project which serve only one purpose. The separable costs of a purpose are the incremental costs of including that purpose in the multiple purpose project. This is the difference between the cost of the multipurpose project and the cost of the project with that particular purpose omitted. For example, the separable cost of flood control in a dual-purpose flood control and water quality project is the cost of the dual-purpose project less the cost of a single-purpose water quality project. Due to economies of scale and complementary among purposes, total cost will normally exceed the sum of the separable costs. This difference is the nonseparable cost. Nonseparable costs include joint and common costs. Joint costs occur when a portion of the project contributes to the production of more than one output. For example, water released from a reservoir for low-flow augmentation may enhance both water quality and navigation. Common costs are indirect or other fixed costs which must be paid but cannot be associated with any production operation. The salary of a supervisor in charge of operating a multipurpose water project is an example of such a cost.

James and Lee (1971) list eight guidelines for selecting a cost allocation method. They stress that there is no correct method, since the choice of method is essentially a successful resolution of conflicting interests.

1) The allocation to any purpose should never be less than the additional cost of including that purpose in the plan nor more than the total benefits provided to the purpose. The cost allocated to a purpose such as flood control, which provides a benefit of 3 and adds 2 to project cost, should be between 2 and 3.

2) The sum of the allocation to all the purposes should equal the total project cost.

3) The allocation method should avoid costly data and complex computations that have no other use. Complex allocation methods are no more correct than simple ones.

4) The allocation process should be straightforward and easily understood. Conflicting interests are more likely to accept compromises they can understand.

5) The amount allocated to each purpose determines the price charged for project services. The cost allocated to an irrigation district will determine how much the district must charge individual irrigators. If the allocation to the irrigation district results in a charge to the individual irrigator approximately equaling the marginal cost of serving him, the irrigator is encouraged to use the economically optimum amount of water.

6) The charges resulting from the allocation should be fairly constant with time in order to provide stability to the market for project goods and services.

7) As cost allocation helps determine user charges, it affects income distribution. Where those served by one purpose are relatively more well to do than those served by another, the equity of the resulting income distribution is an important component in evaluating the allocation.

8) Joint facilities should be operated in accordance with the cost allocation. It is not equitable to allocate most of the cost to a purpose having a low service priority in facility operation.

As can be seen, these guidelines are influenced by the principles of efficiency, fairness, and equity discussed earlier.

Once separable costs have been determined, following the guidance of rule 1 above, nonseparable costs must be allocated to each purpose according to an appropriate measure. The following vehicles have been used for allocating such costs (James and Lee, 1971):

1) Equally among the purposes;

2) Entirely to the high-priority purpose within the limit of benefit the purpose provides;

3) Proportionally to the quantity of use of the facilities for the purpose;

4) Proportionally to the benefit in excess of assigned separable cost to the given purpose;

5) Proportionally to the excess cost required to provide the service by some alternate means;

6) Proportionally to the smaller of the excess benefit or the excess cost of the alternative project.

Different definitions of nonseparable costs have also been used. The most common two are total financial cost less direct costs for the particular purpose and total financial cost less assigned separable costs. The main advantage of using direct costs is that the complex and often controversial computational process required to estimate separable costs can be avoided. However, this method does favor purposes which have large separable and small direct costs.

The appropriateness of each of the above six allocation vehicles depends on the specific situation in which they are used. The principles which were discussed earlier can be used to evaluate the use of a particular rule for a specific case.

Efficiency requires that costs be allocated as closely as possible to actual costs of production, qualified by the cost required to carry the allocation procedure. The assignment of direct or separable costs to each purpose follows this principle. Rules 1 and 2 would be very simple to follow, but would only be appropriate in cases in which each purpose is approximately equal in scope (rule 1) or in which there is one overriding purpose and other very minor ones (rule 2). Rule 3 follows one kind of equity principle (see the discussion of benefit principle above), using a measure of facility use upon which to base charges. This method, called the Use of Facilities Method, is frequently used by the Soil Conservation Service (U.S. Department of Commerce, 1972). Although such an allocation may not limit the cost of a given purpose to the benefit provided, it appeals to fairness by making payment proportional to a visible, physical quantity (low settlement costs). Methods 4, 5, and 6 also incorporate fairness and equity by allocating cost proportionately to alternative measures of benefits less the costs (direct or separable) previously assigned to each purpose. The use of net benefits in rule 4 appeals to fairness and equity; however, there may be difficulties involved in calculating benefits in a clear and concise manner. More will be said about this later. The advantage of rule 5 is that calculation of benefits is avoided by substituting, as a measure of benefits provided, the cost of the cheapest alternative project which can provide the same service. Rule 6 combines rules 4 and 5 by allocating cost according to the smaller of the two benefit measures. This method is the most widely used and has been adopted by the U.S. Inter-Agency Committee on Water Resources (Kaiper, 1971). It is called the Separable Costs-Remaining Benefits Method. The steps recommended by the Department of the Army, Corps of Engineers to carry out this method are as follows (U.S. Department of Commerce, 1972):

1) The benefits of each purpose are estimated.
2) The alternative costs of single-purpose projects to obtain the same benfits are estimated.
3) The separable cost of each purpose is estimated.
4) The separable cost of each purpose in the multi-purpose project is deducted from the lesser of each purpose's benefits or alternative cost. The lesser figure is used since alternative cost is used in this method only if it represents a justifiable expenditure; that is, if it does not exceed the benefits.
5) From total cost of project all separable costs are deducted to determine residual costs.
6) Residual costs, designated as joint costs in this method, are distributed in direct proportion to the remainders found in step 4.
7) To determine the cost allocated to each purpose, the separable and distributed costs for each purpose are added together, and in the case of power the amount of taxes foregone that was used in computing power costs under steps 2 and 3 is subtracted from that sum.

Benefits

As mentioned above, the most widely used cost allocation rules rely on the measurement of benefits from a project which are attributable to a certain purpose. Despite the appeal of this method as reasonable and equitable, it has serious practical limitations. Information about demand or benefit schedules is not easily obtainable. We will review here some of the important problems as they relate to benefits from improved water quality.

Most economists generally agree that willingness-to-pay is the appropriate measure of benfits. The choice facing society is not between clear water and polluted water, for example, but between various levels of pollution. It is the incremental or marginal values that are important in making decisions. The "demand" for water quality (the analog to market demand) is the aggregate of how much individuals will give up (will pay) to enjoy additional increments of improved water quality.

The economic theory for valuing benefits is well developed. A complete theory on the provision and use of public goods, those which are enjoyed in common, such as the water quality of a stream, has been developed. But as is well known, these general principles for management of public good are not so easily applied. The problems of the misallocation of resources and externalities are not theoretical but empirical ones. For instance, there is the problem of the lack of a market. As we said, public goods are enjoyed in common. They are shared and so they are not contained in market transactions and have no market price to use to define demand. The question of intangible benefits is also complex. A hypothetical demand curve can be derived from aggregating individuals' willingness-to-pay (for increased increments of public good, as mentioned above). One approach to estimating willingness-to-pay is to calculate the damages that would occur if a project were not undertaken. However, this method still underestimates psychic benefits (called "intangibles"). In addition, the benefits to a public service such as a multipurpose water resources project cannot be limited to the direct recipients of the service. Indirect or secondary benefits, such as increased employment, accrue to the general public and can be of significant magnitude.

In most cases a complete, thorough analysis is impossible because it is too difficult to estimate the multitude if impacts of, say, a change in water quality. It is particularly difficult to isolate specific pollutants and relate them to a value measurement. The existence of interactions, substitutions, and indirect benefits in most water quality control problems contributes to the difficulty of conducting an adequate analysis as defined by economic theory. Furthermore, data needs are immense and the expense and personnel necessary for data collection are great. These are the greatest impediments to good empirical benefit estimation work. Examples of the types of data used for the various methods of estimating water quality benefits are survey data, property sales prices, detailed studies of physical damages, and origin and destination data from travelers. Many methods use data that must be collected anew for each study. Table E-1 shows alternative methodologies which are appropriate for measuring different water quality benefits (impacts). Depending on the use of the water and the surrounding land uses, certain impacts are of more or less interest to groups of people concerned with water quality. Therefore, it is necessary, using an appropriate methodology, to determine which groups are likely to derive the most benefit from which aspects of improved water quality.[1]

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[1] For a review of recent empirical work pertinent to the estimation of water quality benefits, see Meta Systems Inc, Water Quality Impacts and Socio-Economic Aspects of Reducing Nonpoint Source Pollution From Agriculture (Appendix E), prepared for U.S. Environmental Protection Agency, September, 1978.

TABLE E-1: COMPARISON OF METHODOLOGIES TO MEASURE WATER QUALITY BENEFITS

	Benefit Categories										
Methodology Types	aesthetics	recreation	property values	human health	commercial fishing	agriculture	municipal water supply	industrial water supply	dredging (navigational, flood control)	ecology	local or regional economy
time budget	X	X									
bidding games	X	X		X							
travel costs		X									
marginal costs				medical costs & lost earnings			treatment production costs	treatment production costs	X		
net factor income					yield change x price	yield change x price					
market study			X								
non-dollar measurement	ranking	ranking								change in habitat	
input/output model											X
alternative cost										cost to reproduce	

There are trade-offs involved in choosing a methodology appropriate for use in estimating benefits to water quality groups. The major one is the use of readily available secondary data versus the need for a theoretically valid model which relates specific pollutants to a value measurement. There are more data available for certain benefit categories such as household water supply than for others such as aesthetics. Surveys are expensive and time consuming, but there does not appear to be any feasible alternative, especially for measuring recreation or aesthetic benefits which are two of the major categories of benefits from many multipurpose water resources projects.

Applicability to Stormwater Management

Since many innovative stormwater management projects will provide multiple benefits, the principles discussed above are generally applicable to a consideration of cost allocation among local government agencies and private interests and among agencies at various levels of government. However, most of the on-site control measures applied at a subdivision level are too small individually to justify the elaborate cost-benefit calculations that are undertaken for large multi-purpose water resources projects. It will therefore be necessary to develop cost-sharing rules based upon general notions of costs and benefits for broad classes of projects.

As long as individual localities bear the sole responsibility for stormwater management, it is likely that most will place the full cost on the subdivision developers (and hence the new residents), as is currently the case for conventional drainage. This procedure is justifiable under the benefits received principle and promotes efficient land use decisions, since the residents and developers pay the full cost for developing the site in an environmentally acceptable manner. However, if other levels of government become involved in financing stormwater management facilities, then more complex allocation formulas must be worked out along the lines suggested above.

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GLOSSARY

analysis of covariance: An extension of analysis of variance (see below) which controls for the influence of variables measured on a continuous scale.

analysis of variance: Method by which the total variation of a set of observations (measured by sums of squares of deviations from the mean) is separated into categories associated with the behavior of the variation.

arithmetic mean: The sum of observations in a data set divided by the total number of observations.

average daily traffic (ADT): The average number of vehicles passing a specified point on a roadway during a 24-hour period.

BOD: Biological Oxygen Demand: The quantity of dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter and oxidizable inorganic matter by aerobic biological action. Generally this refers to the standard 5-day BOD test (BOD5).

box and whisker plot: A graphical display of a data set which has a "box" to show the range from upper hinge to lower hinge and "whiskers" or "tails" to show the extreme values.

Central Limit Theorem: In simple form, the theorem states that if n independent samples have finite variances then their sum will tend to be normally distributed as n tends to infinity.

COD: A measure of the oxygen-consuming capacity of inorganic and organic matter present in water or wastewater. It is expressed as the amount of oxygen consumed from a chemical oxidant in a specific test. It does not differentiate between stable and unstable organic matter and thus does not necessarily correlate with biochemical oxygen demand.

column effect: See two-way table.

collinearity: See multicollinearity.

confidence interval: The interval between two values such that the probability of an observation falling within an interval is equal to a specified value.

covariance: A measure of the degree of association between two random variables.

dependent variable: See regression analysis.

deposition: The act or process of settling solid material from a fluid suspension.

design storm: A hypothetical or real storm event which specifies the storm conditions under which storm related structures will be designed to operate successfully.

detention: Temporarily holding storm water on a surface area, in a storage basin or within the sewer system.

deterministic: Containing no random elements, hence completely determined at some fixed point in time.

diagnostic plot: A plot of comparison value versus residuals for each observation for a statistical fit. It is used to define systematic patterns in the residuals.

dummy variable: A variable that takes on one of two values. For example: 0 and 1.

economies of scale: A situation of decreasing costs per unit of production with increasing rates of production.

efficiency: The ratio of the lowest variance feasible to the actual variance of a statistic.

first flush: The condition, often occurring in suspended solids discharges and contained sewer overflows, in which a disproportionately high pollution load is carried in the first portion of the discharge or overflow.

geometric mean: Where n is the number of observations and $x_1, x_2, \ldots x_n$ are the observations, the geometric mean $\bar{G}$ can be shown as:

$$\bar{G} = \sqrt[n]{x_1 x_2, \ldots, x_n}$$

grand mean: See two-way table.

heavy metals: Metals that can be precipitated by hydrogen sulfide in acid solution. For example: lead, silver, gold, mercury and copper.

hinge: upper (lower): The values greater than 75 (25) percent of all observations for a variable.

histogram: A graphical representation of a frequency distribution by means of rectangles whose widths are the class intervals and whose heights are the corresponding frequencies.

hydraulic radius: The cross-sectional area of a stream of water divided by the length of that part at its periphery in contact with its containing conduit; the ratio of area to wetted perimeter.

hydrograph: A plot of discharge (or stage) versus time.

hyetograph: A graph of average rainfall, rainfall excess rates, or volume rates over specified areas during successive units of time during a storm.

independent variable: See regression analysis.

infiltration: The water entering a sewer system and service connections from the ground, through such means as, but not limited to, defective pipes, pipe joints, connections or manhole walls. The movement of water into the ground from the surface.

interaction: Non-additive effects of two or more independent variables on the value of a dependent variable.

interpolation: A process used to estimate an intermediate value of one (dependent) variable when values of the dependent variable corresponding to several discrete values of the independent variable are known.

Kjeldahl Nitrogen: A measure of organic nitrogen content in water and wastewater.

least squares: A technique of fitting a curve close to some given points which minimizes the sum of the squares of the deviations of the given points from the curve.

loading: 1) Accumulation of potential pollutants in a washoff area such as a street; 2) Increase of pollutant concentration in a stream of water.

Manning's Equation: A hydraulic equation which explains flow velocity (v) as a function of hydraulic radius (R), slope (s) and an empirically derived surface roughness coefficient ("Manning's coefficient"), n. The equation commonly appears in the form:

$$v = \frac{1.486\ R^{2/3}\ s^{1/2}}{n}$$

mean: The arithmetic mean of a set of numbers.

mean square deviation: A measure of the extent to which a collection $v_1, v_2, \ldots, v_2$ of numbers is equal; it is given by the expression:

$$(1/n)\ [(v_1 - \bar{v})^2 + \ldots + (v_n - \bar{v})^2]$$

where $\bar{v}$ is the mean of the numbers.

median: Half the data lies above or below this value.

Michaelis-Menton Equation: A growth equation derived from the differential equations used to characterize enzyme-catalyzed reactions.

Monte Carlo Method: A technique which obtains a probabilistic approximation to the solution of a problem by using statistical sampling techniques.

multicollinearity: A problem arising in regression analysis when the same quality is measured by two or more independent variables. It leads to arbitrariness about the allocation of coefficients given to the different variables.

non-conservative: A substance which undergoes chemical or biological transformation in the environment.

non-linear regression: Regression study of jointly distributed random variables where the function measuring their statistical dependence is non-linear.

nonpoint source: Any confined and nondiscrete conveyance from which pollutants are or may be discharged.

pervious: Possessing a texture that permits water to move through perceptibly under the head differences ordinarily found in subsurface water.

polish: To use an iteration technique to find the best estimate of row and column effects in two-way analyses. It is only relevant where the calculation uses an average value other than the mean (e.g., median).

pollutograph: A plot of pollutant concentration (or load) versus time.

porous pavement: A pavement designed to have a high infiltration rate.

probabilistic: Pertaining to random variables.

PUD: Planned Unit Development: A large residential development which locates housing on part of a site, leaving the rest for open space.

R^2: Coefficient of Determination: A standard measure of correlation or explained variation in a regression of two or more variables. Possible values lie between 0 and 1, with 0 indicating no correlation and 1 indicating perfect correlation (no unexplained variation).

random variable: A measurable function on a probability space; usually real valued, but possibly with values in a general measurable space.

regression analysis: Given two or more stochastically dependent random variables, regression functions measure the mean expectation of one (the dependent variable) relative to the other or others (the independent variables).

residual: The difference between an observed value and a value predicted by statistical analysis. Also called "noise" or "unexplained variation."

robust: A characteristic of a statistic that is efficient under a variety of situations.

roof-gutter disconnect: A method of reducing storm water flows by disconnecting roof gutters, thereby allowing otherwise contained storm water to soak into pervious lawn areas.

row effect: See two-way table.

runoff: That part of the precipitation which runs off the surface of a drainage area and reaches a stream or other body of water or a drain or sewer.

scour: The action of a flowing liquid as it lifts and carries away the material on the sides or bottom of a waterway, conduit or pipeline.

sensitivity analysis: Analysis of the sensitivity of model output to changes in the values of input parameters.

skewness: A measure of the departure of a frequency curve from symmetry.

simulation: The representation of a system by a model that imitates the behavior of the system.

sinusoidal: Exhibiting periodic behavior analagous to a sine wave.

Soil Conservation Service method: A procedure for estimating peak runoff for a watershed given certain information on soil types antecedant conditions (i.e., moisture retention factor) and slope.

solids: Total solids; the sum of dissolved and undissolved constituents in water or wastewater, usually stated in milligrams per liter.

spread: The difference between upper and lower hinges, i.e., contains one-half of the data.

standard deviation: A common measure of dispersion equal to the square root of the variance.

stem and leaf diagram: A method of graphically displaying the frequency distribution of a variable.

stochastic: Pertaining to random variables.

STORM: Storage Treatment and Overflow Model: A computer simulation of stormwater runoff developed by U.S. Corps of Engineers Hydraulic Engineering Center.

swale: A wide, shallow ditch, usually grassed or paved.

SWMM: Storm Water Management Model: A model developed by the EPA to generate detailed simulation of the quality and quantity of stormwater during a precipitation event.

transformation: A function between vector spaces.

two-way table: A method of evaluating the effects of two (independent) variables on a third (dependent) variable. The dependent observations are placed in cells of the table. Rows of the table represent the values of one independent variable, the columns represent the categories of the second. The analysis separates the influence of the independent variable (row effect and column effect) from the common value or grand mean.

univariate: A single variable.

variance: A measure of dispersion of a set of numbers from a central tendency equal to:

$$\frac{\Sigma(x_i-\bar{x})^2}{n-1}$$

where x_i are the numbers in the set, $\bar{x}$ is the mean and n is the total number of observations.

CONVERSION FACTORS

U.S. CUSTOMARY TO METRIC

U.S. Customary	Abbr.	Multiplier	Abbr.	Metric Unit
acre	acre	0.4047	ha	hectare
acre-foot	acre-ft	1,233.5	m^3	cubic meter
cubic foot	ft^3	28.32	l	liter
cubic feet per second	cfs	0.02832	m^3/sec	cubic meters per second
cubic inch	in^3	16.39	cm^3	cubic centimeter
cubic yard	yd^3	0.7646	m^3	cubic meter
degree Fahrenheit	°F	(°F-32)/1.8	°C	degree Celsius
feet per minute	fpm	0.005080	m/sec	meters per second
feet per second	fps	0.3048	m/sec	meters per second
foot (feet)	ft	0.3048	m	meter(s)
gallon(s) (U.S. liquid)	gal.	3.785	l	liter(s)
gallons per minute	gpm	0.06309	l/sec	liters per second
inch(es)	in.	2.540	cm	centimeter
inches per hour	in./hr	2.540	cm/hr	centimeters per hour
million gallons per day	mgd	0.04381	m^3/sec	cubic meters per second
mile	mi	1.609	km	kilometer
miles per hour	mph	1.609	km/hr	kilometer per hour
pound(s)	lb	0.4536	kg	kilogram

U.S. Customary	Abbr.	Multiplier	Abbr.	Metric Unit
square foot	ft^2	0.09290	m^2	square meter
square inch	in^2	6.452	cm^2	square centimeter
square mile	mi^2	2.590	km^2	square kilometer
square yard	yd^2	0.8361	m^2	square meter
ton (short)	ton	0.9072	metric ton	metric ton
yard	yd	0.9144	m	meter

CONVERSION OF CONCENTRATION x DISCHARGE TO MASS FLOW RATE

Define:

C = pollutant concentration

Q = wastewater discharge

M = pollutant mass flow rate

Then:

$M\{lb/hr\} = 0.224\ 741 \times C\{mg/l\} \times Q\{cfs\}$

$M\{kg/hr\} = 0.101\ 941 \times C\{mg/l\} \times Q\{cfs\}$

$M\{lb/hr\} = 7.936\ 641 \times C\{mg/l\} \times Q\{m^3/sec\}$

$M\{kg/hr\} = 3.600\ 000 \times C\{mg/l\} \times Q\{m^3/sec\}$